US Army Corps
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Station

Technical Report CHL-99-10
May 1999

# Sedimentation and Hydrodynamic Study of U.S. Coast Guard Station Boat Basin, Port Huron, Michigan

*by Robert R. Bottin, Jr., Gregory L. Williams*





Prepared for U.S. Army Engineer District, Detroit
and U.S. Coast Guard Civil Engineering Unit, Cleveland

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U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
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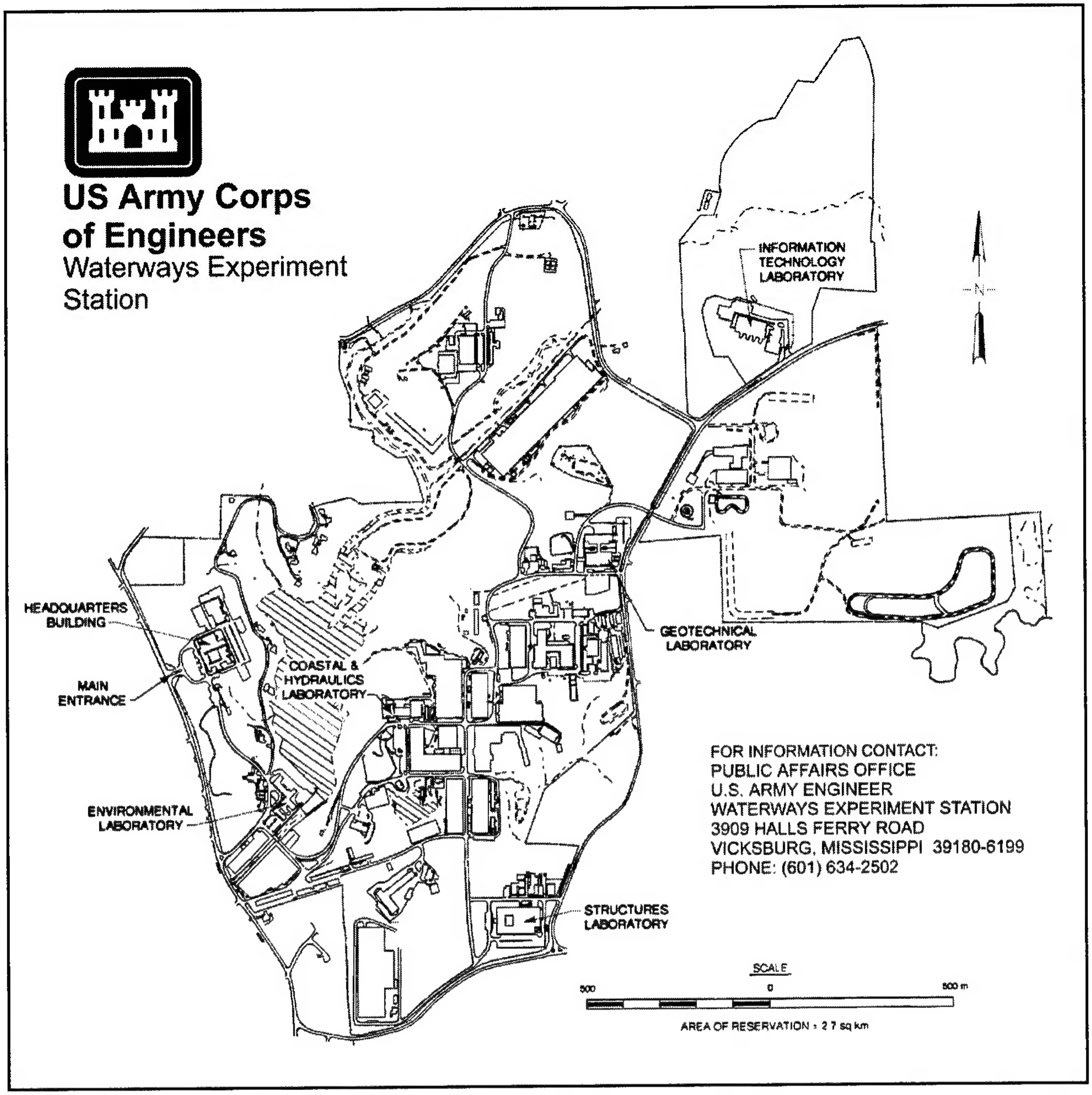
Final report



Prepared for U.S. Army Engineer District, Detroit
Detroit, MI 48231-1027

and U.S. Coast Guard Civil Engineering Unit, Cleveland
Cleveland, OH 44199-2060

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# Preface

A request for an investigation of entrance shoaling problems and undesirable wave conditions at the U.S. Coast Guard (USCG) Station Boat Basin, Port Huron, Michigan, was initiated by the U.S. Army Engineer District, Detroit. Authorization for the U.S. Army Engineer Waterways Experiment Station (WES), Coastal and Hydraulics Laboratory (CHL), to perform the study was subsequently granted by the Headquarters, U.S. Army Corps of Engineers. The study was performed on a reimbursable basis, and the sponsor was the USCG Civil Engineering Unit, Cleveland. Funds were provided by the Detroit District during September and October 1997. WES is a complex of five laboratories of the Engineer Research and Development Center (ERDC).

Field and laboratory investigations were conducted during the period October 1997 through November 1998 under the direction of Dr. James R. Houston and Mr. Charles C. Calhoun, Jr. (retired), Director and Assistant Director of CHL, respectively. Field investigations and analyses were conducted by Mr. Gregory L. Williams, Coastal Evaluation and Design Branch (CEDB), CHL, under the direct guidance of Mr. Thomas W. Richardson, Chief, Coastal Sediments and Engineering Division, CHL, and Ms. Joan Pope, Chief, CEDB. Mr. Jeff Lillycrop, CEDB, conducted the Scanning Hydrographic Operational Airborne LIDAR Survey of lower Lake Huron. The laboratory experiments were conducted by Messrs. Hugh F. Acuff, Cecil Dorrell, and William Henderson under the supervision of Mr. Robert R. Bottin, Jr., Harbors and Entrances Branch (HEB), CHL, and the direct guidance of Mr. C. E. Chatham, Jr., Chief, Navigation and Harbors Division (NHD), CHL, and Mr. Dennis G. Markle, Chief, HEB. Ms. Rebecca M. Brooks, NHD, conducted the wave hindcast study at the site. This report was prepared by Messrs. Bottin and Williams.

During the course of the investigations, liaison was maintained by means of conferences, telephone communications, e-mail, and periodic progress reports. The following personnel visited WES to attend conferences and observe model operation during the course of the study.

| | |
|---|---|
| James Selegean | Detroit District |
| Michelle Thrift | Detroit District |
| Gregory Lodge | USCG Civil Engineering Unit, Cleveland |
| Tom Bennett | Michigan Department of Environmental Quality (DEQ) |
| Tom Kolhoff | Michigan DEQ |

COL Robin R. Cababa, EN, was Commander of ERDC at the time of publication of this report. This report was prepared and published at the WES complex of ERDC.

# Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| acres | 4,046.856 | square meters |
| cubic feet | 0.02831685 | cubic meters |
| cubic yards | 0.7646 | cubic meters |
| degrees (angle) | 0.01745329 | radians |
| feet | 0.3048 | meters |
| inches | 2.54 | centimeters |
| miles (U.S. statute) | 1.609347 | kilometers |
| pounds (mass) | 0.4535924 | kilograms |
| square feet | 0.09290304 | square meters |
| square miles | 2.589998 | square kilometers |
| tons (2,000 pounds, mass) | 907.1847 | kilograms |

# 1 Introduction

The U.S. Coast Guard (USCG) Station, Port Huron, is located in Port Huron, Michigan, at the extreme southern portion of Lake Huron where the lake empties into the St. Clair River (Figures 1, 2, and 3). This location is ideal for the USCG to conduct rescue operations for the heavy summer recreational boat traffic on lower Lake Huron and the upper St. Clair River. However, because the station is located in the dynamic lake-to-river transition region, sediment shoaling is so severe that rescue operations from the station's boat basin are limited and frequent dredging is required. The existing boat basin configuration is designed to berth a 12.5-m (41-ft)[1] vessel (which draws approximately 1.5 m (5 ft)), but because of the sedimentation, the USCG can only operate its rigid hull inflatable boat.

Since the present basin was constructed in 1996, dredging is required approximately every 3 months. In addition, the existing configuration and type of construction (vertical sheet-pile walls) contribute to undesirable reflective wave energy inside the basin from wind waves and vessel-generated waves from ship traffic. Strong currents in combination with waves also cause problems for navigating into the basin.

The USCG wants to identify a solution that will reduce the dredging frequency and improve navigation into and out of the basin as well as improve mooring of vessels at the basin dock. In recent years, the USCG has sought U.S. Army Corps of Engineers (USACE) permits for multiple dredging operations, but no long-term plan had been identified to address the chronic sedimentation and wave energy problem. At the suggestion of the U.S. Army Engineer District, Detroit, and the Michigan Department of Environmental Quality (State permitting agency), the USCG through the Detroit District contracted with the U.S. Army Engineer Waterways Experiment Station (WES) to study the entrance sedimentation and harbor resonance problems and make recommendations on steps to take to reduce shoaling at the basin entrance and minimize harbor wave action.

The objective of the WES study was twofold: (a) conduct field investigations to collect data to analyze existing coastal processes, and (b) conduct a physical

[1] Units of measurement in the text of this report are shown in SI units, followed by non-SI (British) units in parentheses. In addition, a table of factors for converting non-SI units of measurement used in figures, tables, plates, and photographs in this report to SI units is presented on page viii.

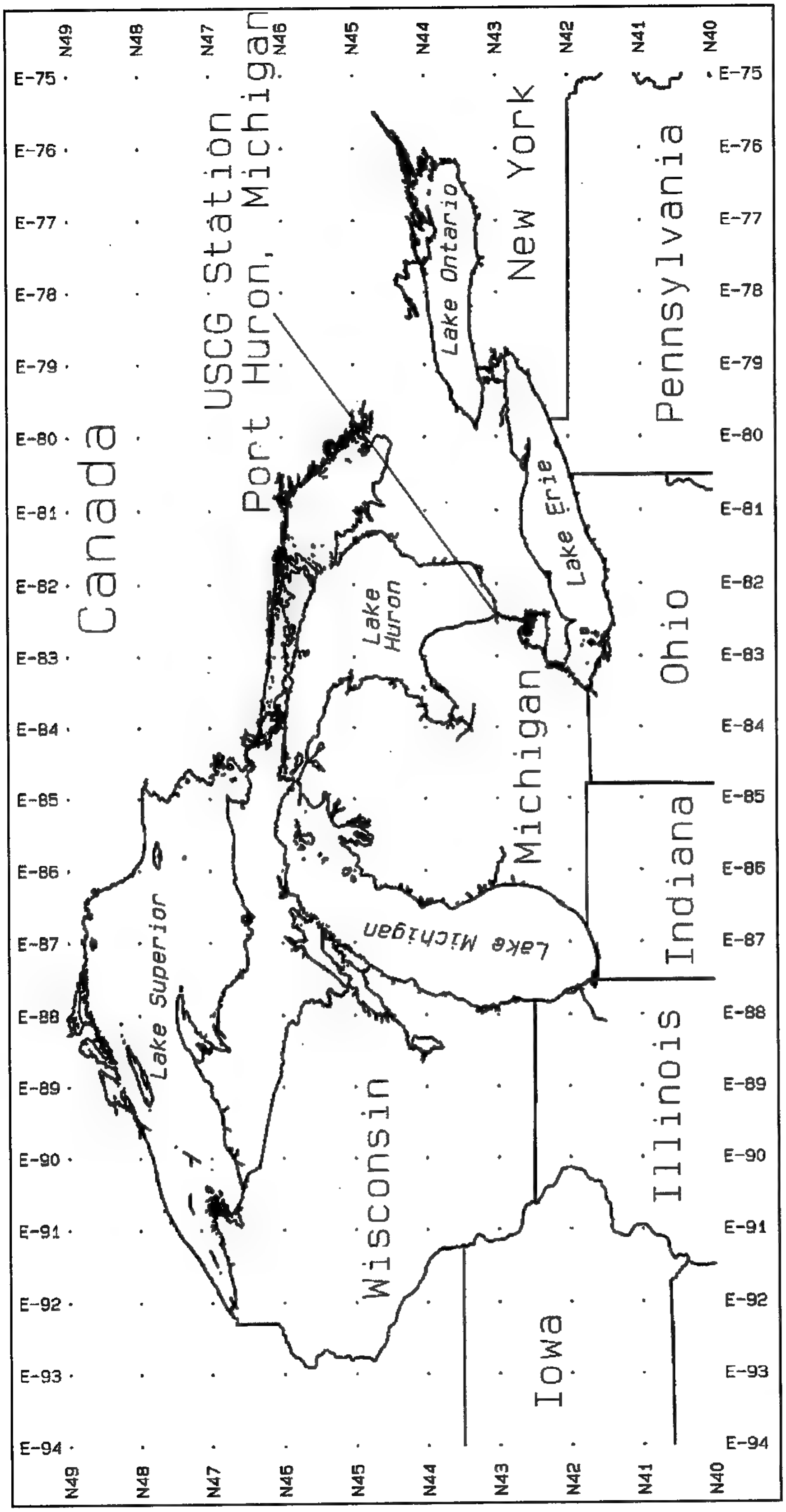



Figure 1. Project location map

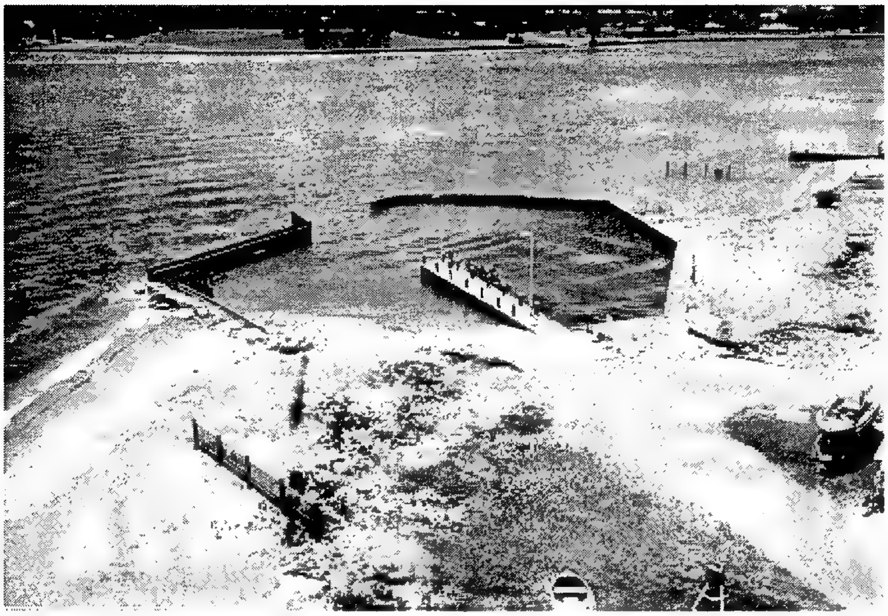


Figure 2. USCG Station, Port Huron, boat basin

Figure 3. Area north of USCG Station, Port Huron

model study to qualify sediment transport and quantify wave resonance inside the boat basin. The field investigations included measuring currents along 11 transects with an acoustic Doppler current profiler (ADCP), a sediment sampling, a hydrographic survey, and a video tape of vessel traffic near the boat basin. This information was to be used to quantify the hydrodynamic forces responsible for sediment transport at the study site and to serve as calibration for the physical model.

The physical model was constructed at 1:60 scale and covered lower Lake Huron from approximately 700 m (2,300 ft) north and northeast of the boat basin to approximately 460 m (1,500 ft) southwest of the boat basin in the St. Clair River. Two types of model investigations were conducted on 10 boat basin configurations—(a) a sedimentation study using a coal tracer to track the sediment movement pathways and deposition areas with respect to the boat basin, and (b) wave measurements inside the basin to document the optimum configuration for reducing reflective wave energy.

# 2 Background

Lake Huron is the fifth largest inland body of water in the world and second largest in North America with a surface area of 59,600 sq km (23,010 square miles). Its maximum depth is 229 m (750 ft), and it drains an area of approximately 129,500 sq km (50,000 square miles) (Hough 1958). Except for a small amount of water diverted from Lake Michigan at Chicago into the Illinois River, the entire upper Great Lakes system (Lake Superior, Lake Michigan, and Lake Huron) discharges through Lake Huron and into the St. Clair River, Lake St. Clair, the Detroit River, and Lake Erie. Lake Michigan and Lake Huron are connected by the Straits of Mackinac and have the same water level. The surface of Lake Superior is approximately 6.1 m (20 ft) higher than that of Lakes Michigan and Huron and is connected to Lake Huron by the St. Marys River, which contains a series of locks and canals (Hough 1958).

The Great Lakes do not experience astronomical tides, but water-level fluctuations are common as a result of storms, wind, and barometric pressure differences. Fluctuations in the still-water level result from seasonal precipitation patterns and snowmelt runoffs and over longer time periods in response to large-scale weather patterns. In general, the Great Lakes water levels are highest in the spring and summer and lowest in the winter. Figure 4 shows historic water levels of Lake Huron. Because the Great Lakes are composed of fresh water, ice is common throughout the system. Shore ice can extend up to 2 km (1.2 miles) offshore, and on occasion ice can cover an entire lake. Mobile ice fields and ice flows can cause damage to coastal structures.

The study site at Port Huron, Michigan, is located on the western shore of Lake Huron just as the lake narrows into the St. Clair River. This transition region is highly dynamic with strong river currents (depth-averaged velocities in excess of 1.8 m/sec (6 ft/sec) just north of the Blue Water Bridge and 0.9 to 1.2 m/sec (4 to 5 ft/sec) in the vicinity of the boat basin).

Two shoaling studies have been conducted for the boat basin at Port Huron. The USCG Academy conducted the first study in 1974 (USCG Academy 1974). A subsequent study was conducted by the USCG Civil Engineering Unit, Cleveland (CEU Cleveland), in 1991 (CEU Cleveland 1991). These reports are summarized below:

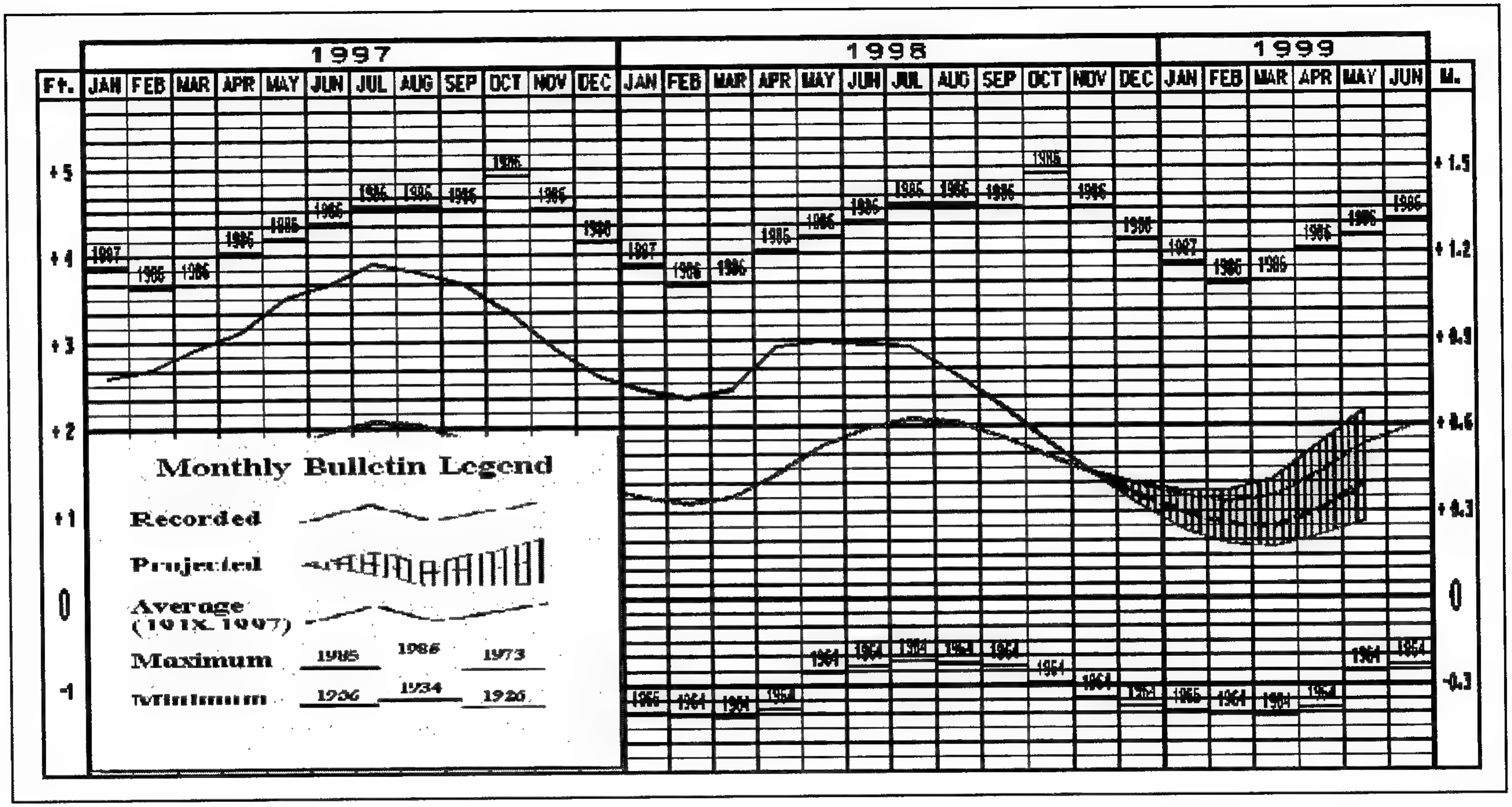



Figure 4. Lake Huron historic seasonal water levels (Chart Datum 575.5 ft or 175.0 m) (from the Detroit District Monthly Bulletin of Great Lakes Water Levels web site—*http://huron.lre.usace.army.mil/levels/bltnhmpg.html)*

## USCG Academy (1974)

The problem statement says currents in the vicinity of the basin are 1.03 to 1.54 m/sec (3.4 to 5.1 ft/sec) and up to 3.09 m/sec (10.1 ft/sec) under the Blue Water Bridge. The boat basin was constructed in 1931 in its present location with wood pilings spaced 1.2 to 1.8 m (4 to 6 ft). In 1940, steel sheetpiling was added north and east of the pilings to provide protection for boat launches from waves. No record of dredging the basin was found prior to installation of the sheet piles. Since its enclosure, the boat basin has required almost annual dredging. Often boat prop wash has been used to help remove deposited sediment.

Three mechanisms are assumed as a means for sediment to enter the boat basin:

*a.* Littoral transport of suspended and bed load moving along the shoreline just lakeward of the breakwater provides the material composing a bar across the mouth of the basin.

*b.* Wave overtopping carries a range of particles over the breakwall (up to "fist-sized" cobbles.

*c.* Suspended sediment travels into the boat basin and ultimately settles out in the quiescence of the boat basin.

Proposed solutions include relocating the station, moor vessels in more protected areas along the St. Clair River, use dry boat launches, or use air-cushioned vessels. USCG Academy (1974) states:

> "There appears no easy solution from a scientific/engineering standpoint. The situation that exists does not appear solvable by any known method of boat basin configuration. Any alteration of the southern end of the north-south breakwater could cause the creation of eddies and vortex shedding that does not now exist."

The recommended solution was to revert to an open mooring whereby the breakwaters would be removed allowing littoral transport to move through the boat basin area. During summer months when protected waters were needed for vessel operation, a semiportable breakwater could be installed on outer pilings. After the boating season concluded, this breakwater system could be removed to allow unimpeded littoral transport.

A test of this concept was conducted whereby part of the breakwater system (northern section) was removed allowing southward-moving riverine currents to flow through the basin. Because this test was not of the fully open mooring plan that was recommended (i.e., the eastern breakwall remained, preventing wave action to help move sediments alongshore), increased sedimentation occurred—currents alone were not enough to keep the mooring area flushed clean.

## CEU Cleveland (1991)

CEU Cleveland (1991) provides a history of the basin after the USCG Academy (1974) report up to 1991. In 1975, 34 sheet piles 17.1 lineal m (56 lineal ft) were removed from the north breakwater as the test recommended by USCG Academy (1974). The area behind the breakwater filled with sediment to record heights. In 1976, all additional timber piles were removed and a channel dredged. In 1978, a channel was dredged to –2.4 m (-8.0 ft) low water datum (LWD),[1] and a new floating dock was installed. In 1979, the channel filled in from the north entrance, and a plan was made to close off the northern opening and provide a pump to perform maintenance dredging. In 1980, this plan was abandoned and instead 2,141 cu m (2,800 cu yd) of material was removed. In 1981, the basin was abandoned and the USCG vessel was moved to a temporary facility on the Black River. No active basin existed at the site from this time up through the preparation of the CEU Cleveland (1991) report.

The CEU Cleveland (1991) report was prepared to identify possible solutions to the shoaling problem to allow a basin to be rebuilt at the original location. These options are summarized below.

*a.* Move the station.

*b.* Build open moorings and dredge to conform to the natural slope upstream and downstream of the station.

*c.* Build open moorings as in *b* above, plus install a removable floating wave damper (similar recommendation as the USCG Academy (1974) report).

*d.* Enclose the moorings with a sheet-pile wall as was done prior to 1974. Increase the height of the sheet-pile wall to reduce overtopping. Annual dredging would be required to keep the mouth of the basin open.

*e.* Enclose the entire mooring on the north and south with sheet-pile wall and dredge a new mooring area south of the south sheet-pile wall.

*f.* Remove all sheet-pile walls and build a haul-out boat slip.

[1] All elevations cited herein are in meters (feet) referred to low water datum (LWD). LWD on Lake Huron is 176 m (577.5 ft) above the International Great Lakes Datum (IGLD) of 1985.

# 3 Field-Data Collection

To support the sedimentation analysis and physical model study, field data were collected in July and September/October 1997. A hydrographic survey was conducted 18 July 1997, and from 29 September to 1 October 1997 current data, sediments, and video footage were collected. Additional current measurements were made on 8 October 1997.

## Hydrographic Survey

A Scanning Hydrographic Operational Airborne LIDAR Survey (SHOALS) bathymetric survey of lower Lake Huron was conducted by the Joint Airborne Lidar Bathymetry Technical Center of Expertise. The survey area included Lake Huron bank-to-bank from approximately 1.6 km (1 mile) north of the USCG Station to approximately 305 m (1,000 ft) south of the Station along the St. Clair River. SHOALS surveys are collected from a Bell 212 helicopter using light detection and ranging (LIDAR) technology whereby a laser beam is projected from a pod beneath the helicopter. Part of this laser light is reflected from the water surface, which locates the water-surface elevation. Light that is not absorbed in the water is reflected off the bottom, and the difference between the bottom- reflected light and the surface-reflected light gives the water depth. SHOALS uses kinematic on-the-fly global positioning system technology to cover large areas rapidly and produces over 115,000 soundings per square kilometer. Flight data are processed in a trailer-based mobile facility to produce final project maps and charts. SHOALS surveys comply with vertical accuracy standards of ±15 cm (0.5 ft) and horizontal accuracy of ±3 m (9.8 ft) (Lillycrop, Parson, and Irish 1996).[1]

This survey was used to characterize the bathymetry of the study site and provide depths for construction of the physical model. Latest SHOALS development allows topographic survey information for subaerial regions around the project site. Figure 5 is a bathymetric map of lower Lake Huron from the SHOALS survey. The lines shown are reference locations for current transects as described below. Figure 6 is a bathymetric map of the USCG boat basin and the

[1] Joint Airborne Lidar Bathymetry Technical Center of Expertise and SHOALS web page at: *http://shoals.sam.usace.army.mil/.*

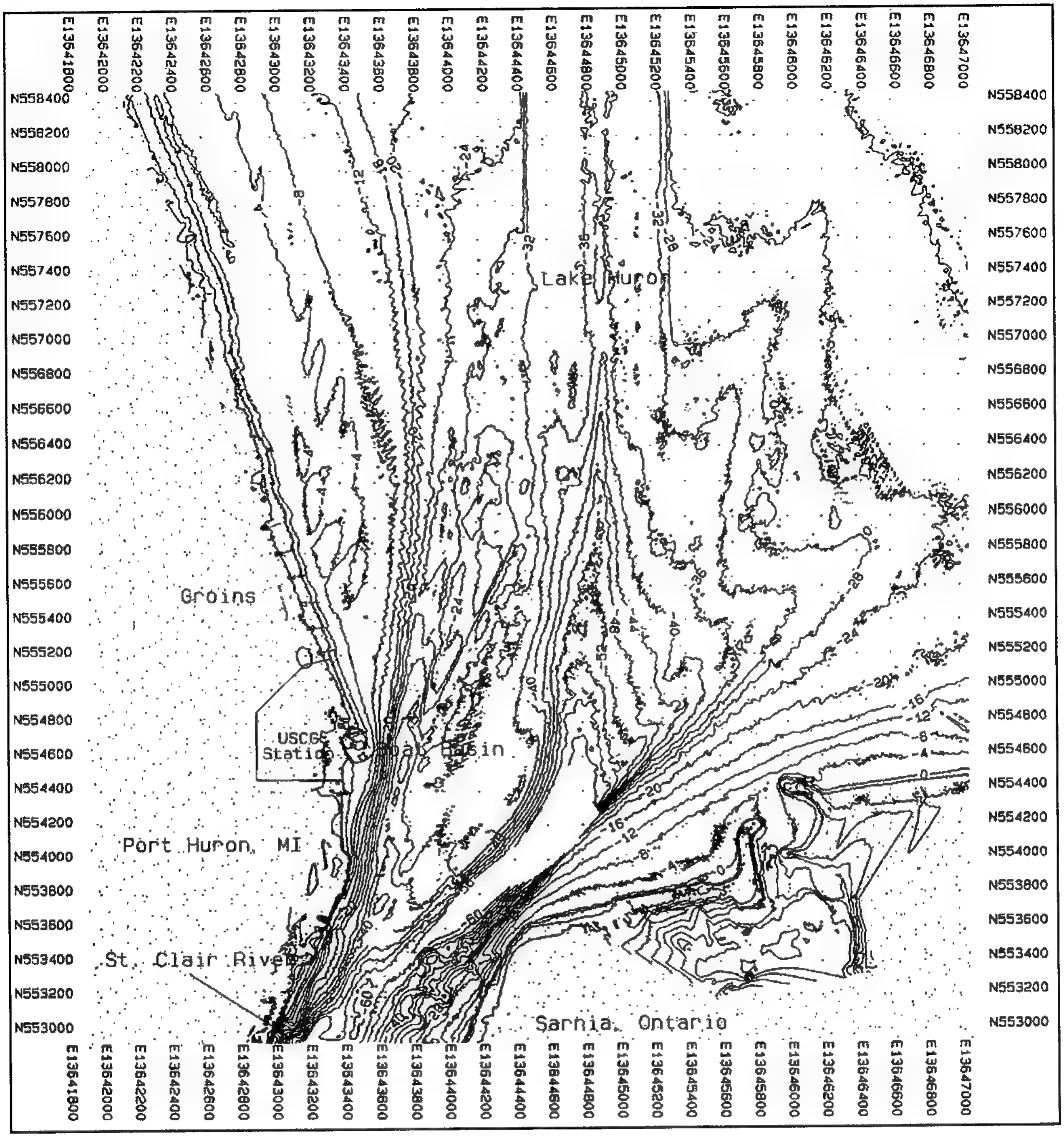



Figure 5. Bathymetry of lower Lake Huron from SHOALS survey on 18 July 1997 (Note: Vertical control is feet referenced to LWD ; horizontal control is feet referenced to Michigan State Plane South. Units are English (i.e., feet) to maintain consistency with the data as collected by SHOALS)

immediate surrounding area. Depths in feet on both maps are referenced to LWD for Lake Huron.

One area southeast of the boat basin had depths in excess of 18 m (60 ft) that were beyond the light-penetration range of the SHOALS system for the given

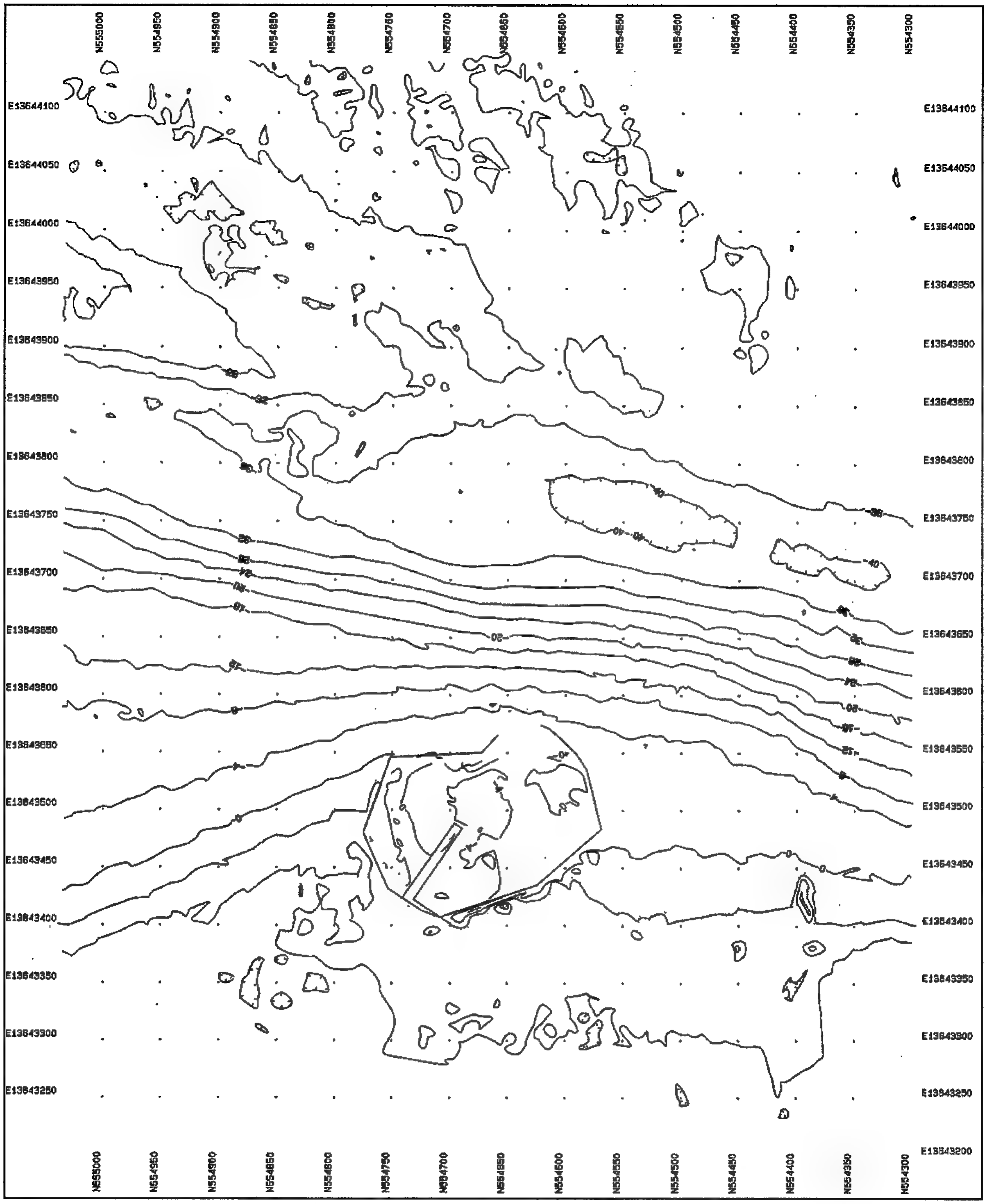


Figure 6. Bathymetry survey of USCG Station boat basin from SHOALS survey on 18 July 1997 (Note: Vertical control is feet referenced to LWD; horizontal control is feet referenced to Michigan State Plane South. Units are English (i.e., feet) to maintain consistency with the data as collected by SHOALS)

water clarity conditions at the time of the survey. Other bathymetric features observed in Figure 5 are a series of shoals north of the boat basin running in an almost north-south direction and a very steep descent into the river channel from terraces on either side. Based on sediment sampling (discussed below), this area is primarily characterized by sand. These types of linear shoals are typical for riverine (steady, but high, flow) type environments. The navigation channel is also observable in the north-central portion of Figure 5 and appears to lead directly into the deep area beyond measurable depths. A second deep area (depths of 12.2 m (40 ft)), located just offshore of the boat basin, is separated from the 18+ m (60+ ft) area by higher relief (approximately 8.5 to 11.0 m (28 to 36 ft) deep).

## Current Measurements

During the September/October field-data collection effort, currents were measured to identify the magnitude of flows in the vicinity of the boat basin. Depth-averaged currents were used to calibrate/verify the physical model, and bottom currents extracted from the data sets were used to compute theoretical potential sediment-transport rates.

Currents were measured with an ADCP along transects shown in Figure 7. An ADCP transmits acoustic pulses from a transducer assembly into the water column. ADCPs can either be bottom mounted "looking" up or deployed from a floating vessel "looking" down. The transducers receive backscattered signals from particles that move with the water currents. Velocities are derived by the Doppler effect whereby the transmitted signal changes frequency with respect to the ADCP and particle movement. These frequency changes are directly proportional to current velocities providing a two-dimensional image of the current field.

During this field study, the ADCP was deployed from a 6.1-m- (20-ft-) long boat provided by the Detroit District. Surveys were conducted along the transects shown in Figure 7 on 29 and 30 September and 8 October. Only Transect C1 was surveyed on 29 September; all transects were surveyed on 30 September and/or 8 October. Figures 8 and 9 show depth-averaged current vectors (direction and magnitude) for each survey on 30 September and 8 October, respectively. The absence of data on any one transect indicates that the transect was not surveyed on that day. Because data from multiple transect surveys were similar and for clarity, only one survey is shown per day on Figures 8 and 9. No currents were measured on 1 October because of adverse weather.

Current measurements showed that the strongest flows south of the boat basin were at the head of the St. Clair River (Transects C1 and C2). These depth-averaged flows near the center of the channel exceeded 1.8 mps (6 fps) on the day of the measurements. Velocities near the boat basin ranged from nearly 1.8 mps (6 fps) at Transect 3 just south of the basin to around 1.2 mps (4 fps) at Transect C4 north of the basin. Velocities continued to decrease with distance north having magnitudes on the order of 0.6 mps (2 fps).

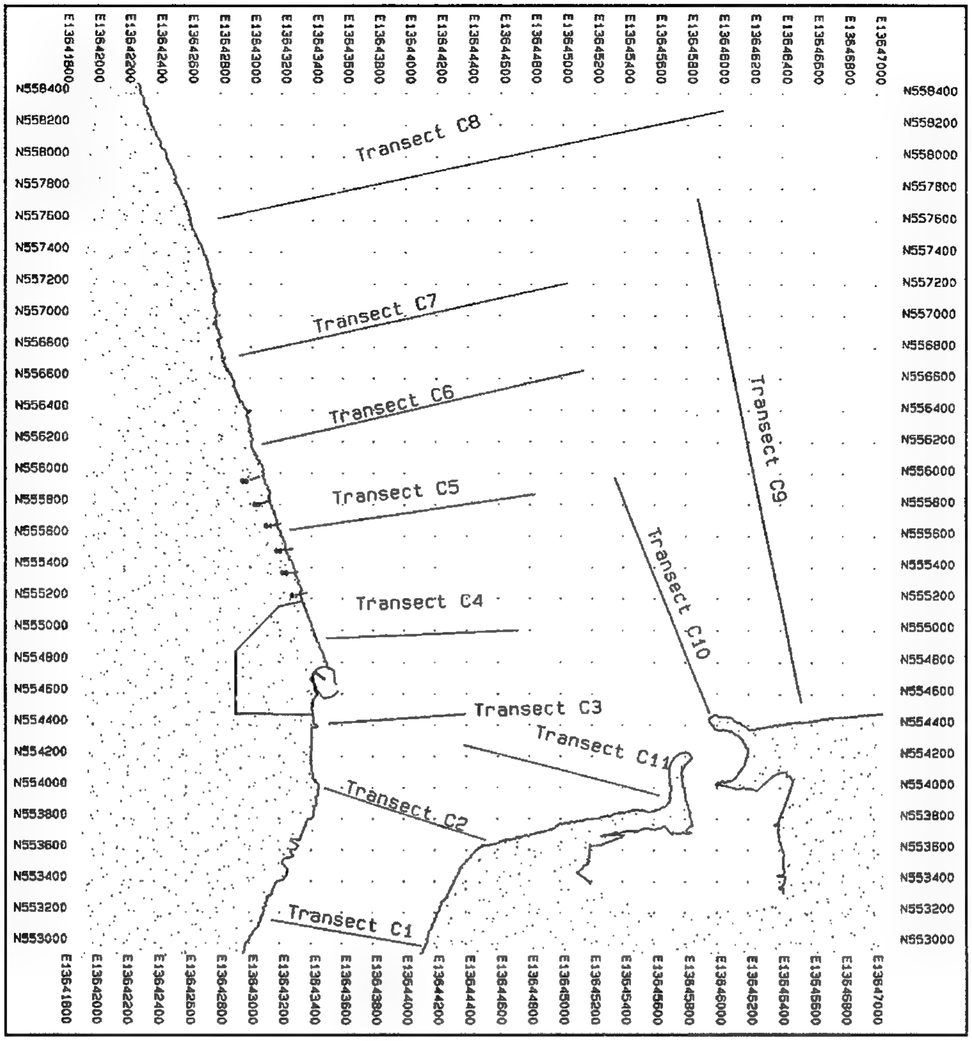



Figure 7. ADCP current transects

Near-bottom velocity vectors along each transect are shown in Figures 10 and 11. The velocities are taken from the ADCP reading closest to the bottom. On average, this depth was approximately 0.3 to 0.6 m (1 to 2 ft) above the actual bottom. Comparing Figures 10 and 11 with Figures 8 and 9, one can see how the bottom velocities compare with overall depth-averaged velocities. Bottom depths at each location along the transects shown in Figures 10 and 11 can be inferred from the SHOALS bathymetry survey in Figure 5.

As expected, the bottom-velocity magnitudes were smaller than the depth-averaged magnitudes, with velocities less than 0.61 mps (2 fps) at some locations for Transect 1. Transects 2 and 3 had bottom velocities around 1.2 mps (4 fps). Transects 2, 3, and 4 all show velocity vectors in the southwest direction probably indicative of a flow split around either side of the high-relief area discussed above in the SHOALS bathymetry section.

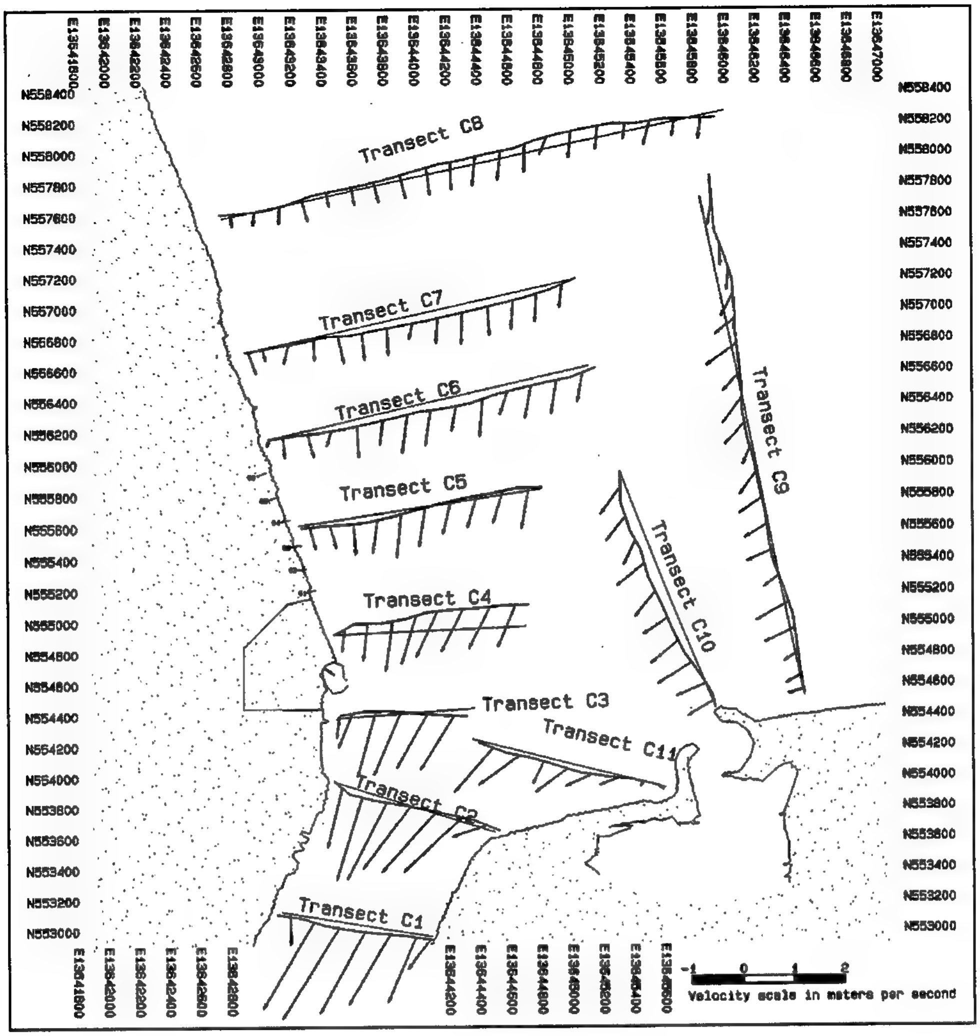



Figure 8. Depth-averaged current vectors along each transect for 30 September 1997

Field-data collection was during a period of higher than average high water for Lake Huron. Water levels are typically higher during the spring/summer, and from July when the SHOALS survey was flown through September/October when the field-data collection was conducted, lake levels were approximately 0.6 m (2 ft) above the long-term average. This means that average currents at Port Huron are probably less (and subsequent sediment-transport capacity lower) than that measured. In addition, the depths inside the boat basin are larger than would be expected for an average year without dredging.

## Sediment Samples

Sediment samples were collected on 1 October 1997 north of the boat basin (beach and nearshore), inside and outside of the boat basin, and in the areas east and south of the basin. Figure 12 shows the 58 sample locations with $D_{50}$ grain size. All subaqueous samples were collected with a clamshell sampler deployed

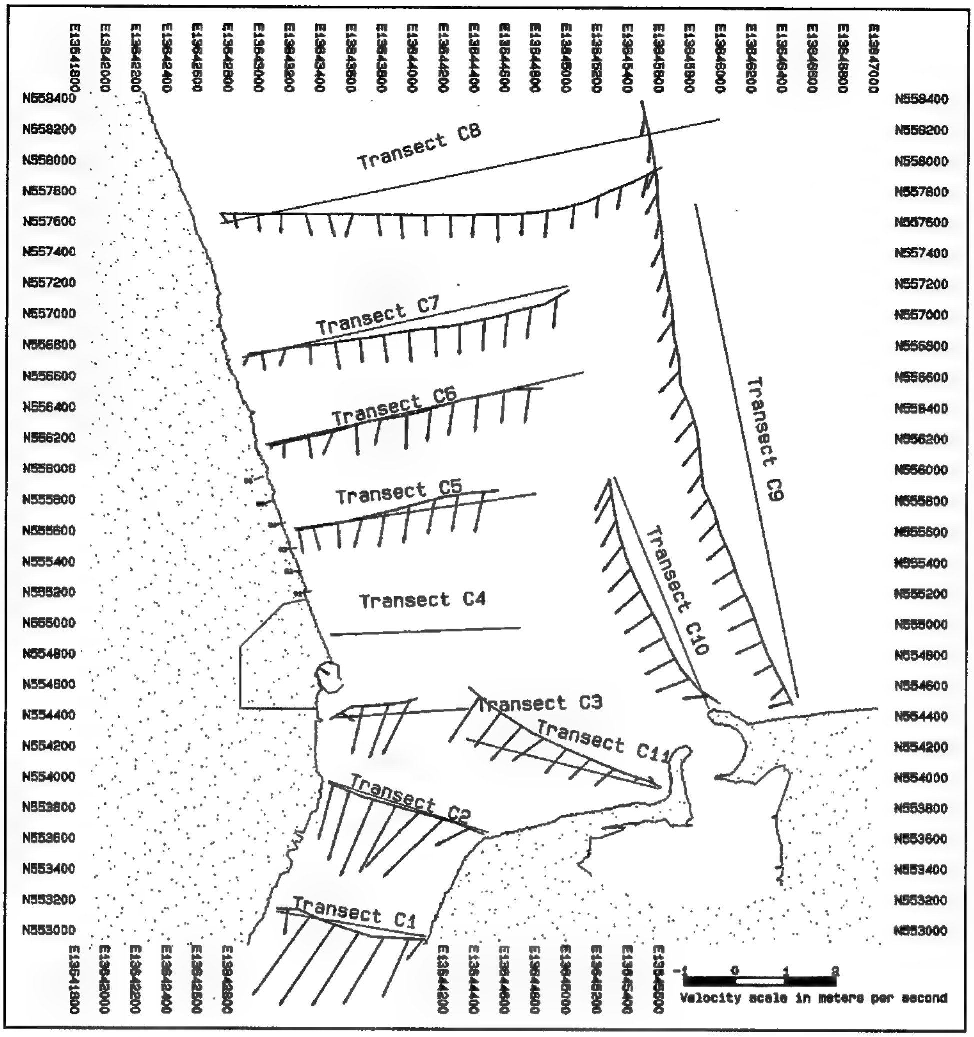



Figure 9. Depth-averaged current vectors along each transect for 08 October 1997

from the Detroit District 6.1-m- (20.0-ft-) long boat and hoisted with a hand-operated winch.

Grain-size distributions and sample statistics (including $D_{50}$) were obtained for each sample. Some of the samples were too small to provide statistically accurate grain-size distributions because they contained large cobbles in excess of 20 mm (0.79 in.) in diameter. For demonstration purposes and to identify areas consisting of "large" sediments versus "small" sediments, all samples (and sample statistics) were assumed statistically valid. Figure 13 is sediment-size distribution plot showing where sand and cobbles predominate.

Bottom-type characteristics cannot be determined solely from sediment samples, so it is possible that some of the "large" samples actually indicate glacial till where a few of the larger particles were gathered by the sampler. Therefore, it is difficult to know whether these larger particles are part of a glacial till that has

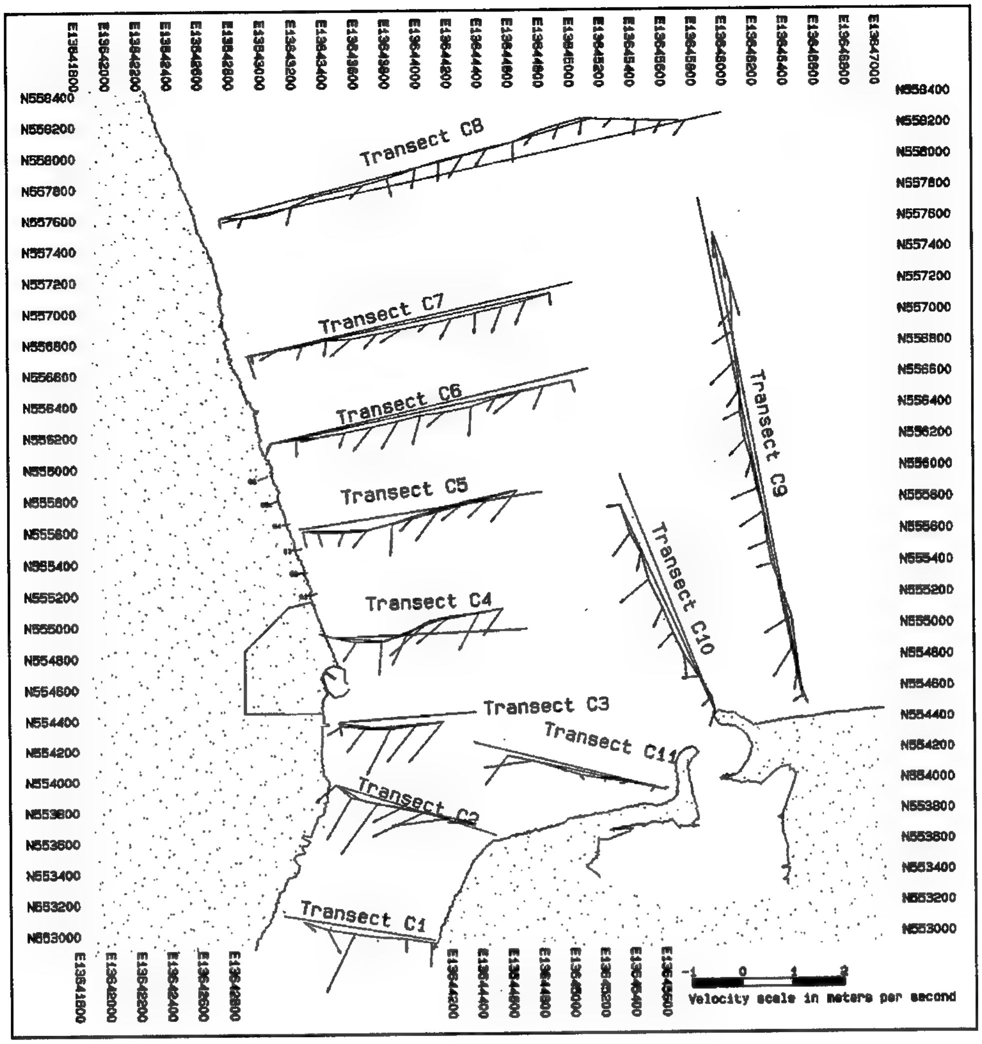



Figure 10. Near-bottom current vectors along each transect for 30 September 1997

been exposed by the erosion of overlying sand and gravel or whether they are hydraulically mobilized. Because grain sizes of the samples at the basin entrance (an area often requiring dredging) are "large," it is likely that even if there is an exposed glacial till in the vicinity, large cobbles, whether liberated from the till or from other sources, are mobilized and transported southward.

Figure 12 shows that most of the sediments inside the basin are small with $D_{50}$s ranging from 0.25 to 16 mm. A line of coarse material ($D_{50}$s ranging from 16 to 32 mm) exists between 18.3 and 27.4 m (60 and 90 ft) offshore to the north of the basin. Fine-to-medium sand exists further offshore to the northeast of the basin, while coarser material occurs closer to the basin and to the southeast.

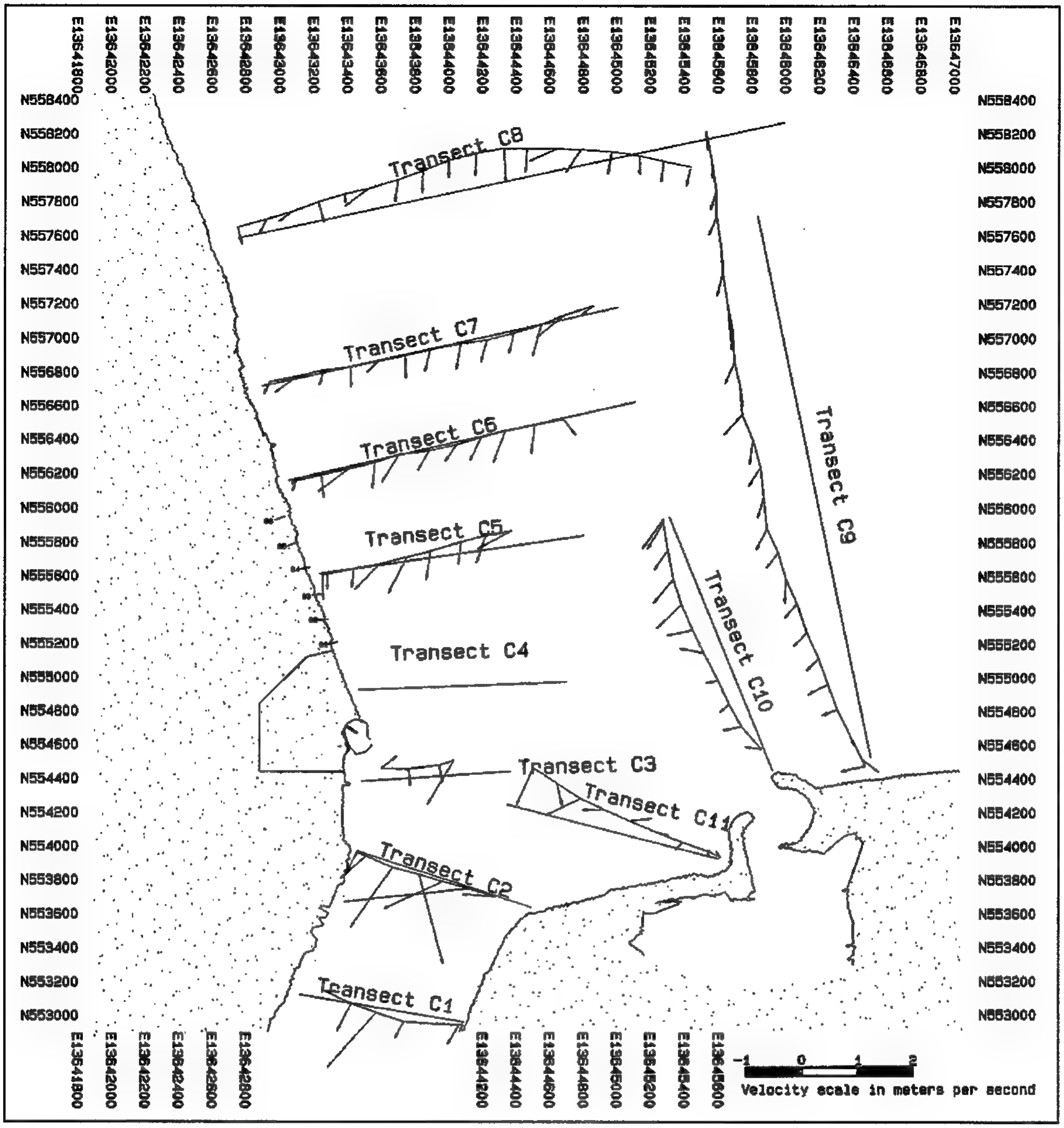



Figure 11. Near-bottom current vectors along each transect for 08 October 1997

## Video Tape

During the course of the field study, a video camera was placed at the top of Fort Gratiot Lighthouse to record vessel traffic and observe vessel-generated wave characteristics that resulted both offshore and within the basin for various vessels and transit directions. Twelve hours of recording on six tapes were obtained on 30 September and 1 October 1997. A total of 18 vessels varying from small recreational boats to large freighters were recorded transiting by the boat basin. Table 1 summarizes the vessel name, type, length, draft, direction of transit, and

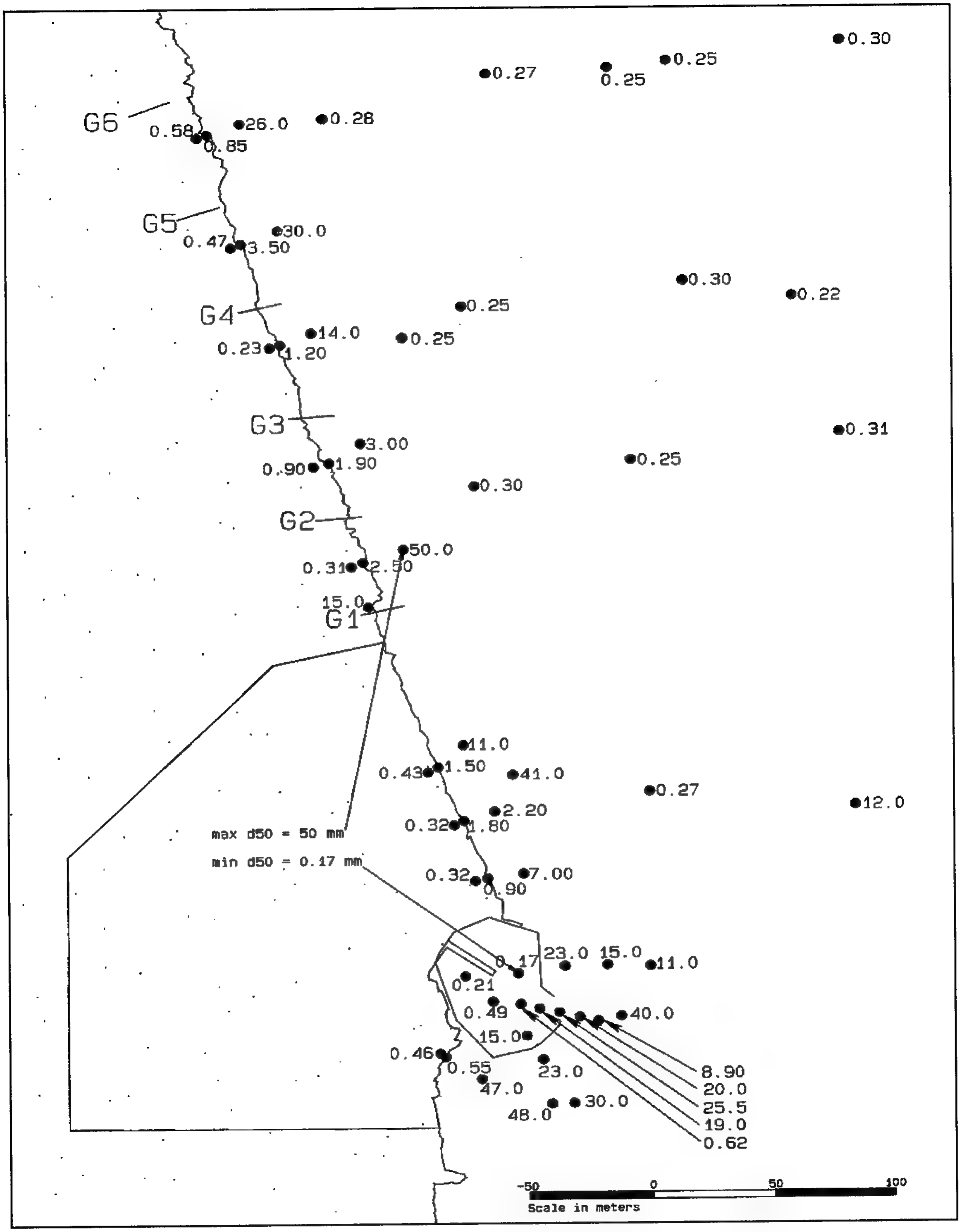



Figure 12. Sediment-sample locations and $D_{50}$ grain size

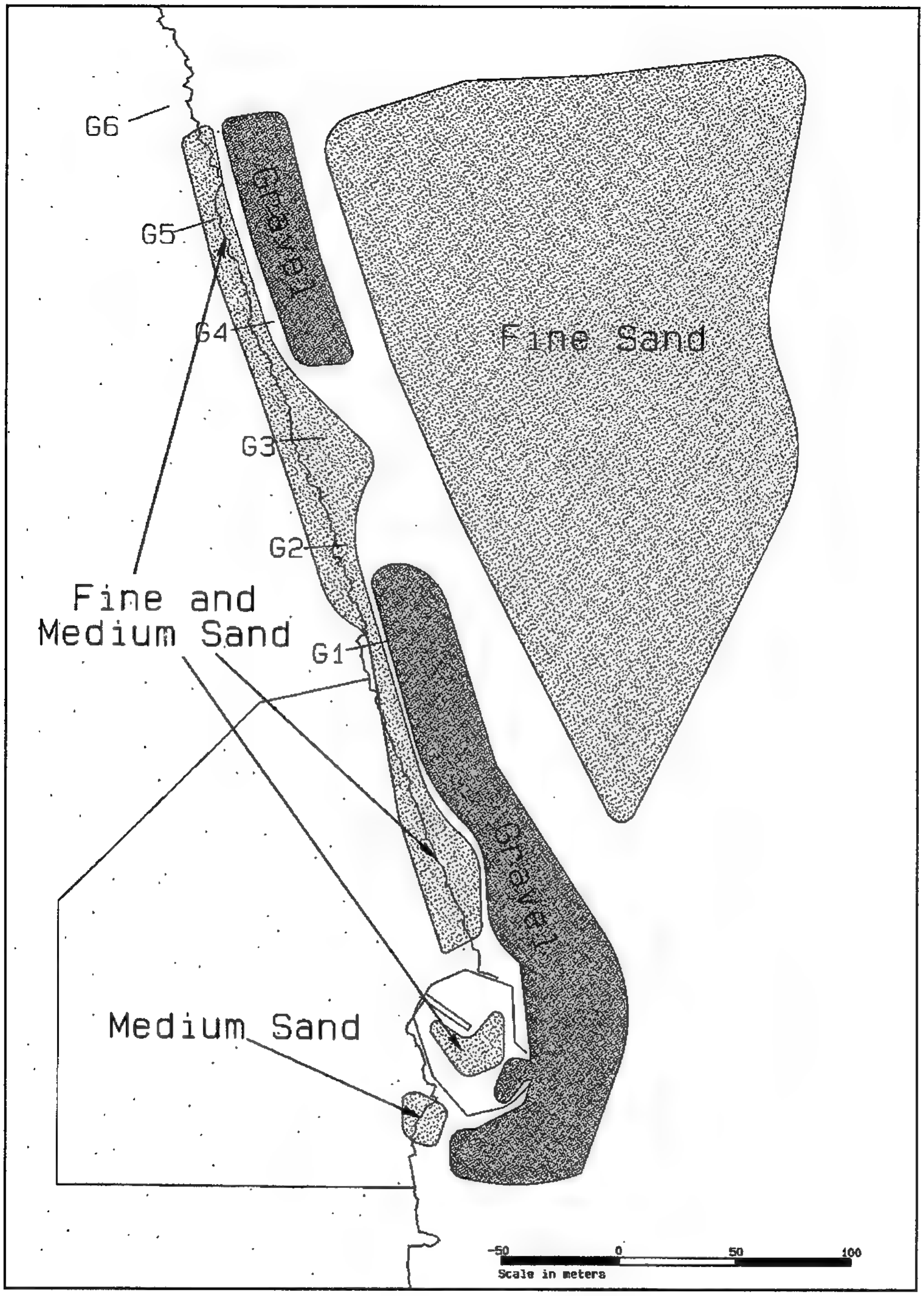



Figure 13. Sediment-size distribution

date/time of each vessel as well as relative wave observations in the boat basin resulting from the passing vessel.

The video record indicated that small (greater velocity) southbound vessels had more impact on wave energy entering and disrupting mooring inside the boat basin. This observation is supported, in part, by comments from the USCG staff stationed at Port Huron who commented that southbound traffic caused the

**Table 1**
**Vessel Traffic During 30 September - 01 October 1997 Field-Data Collection**

| Type | Approximate Length | Direction | Date/Time | Waves[1] |
|---|---|---|---|---|
| Ship-barge pushed by tug | | North | 9/30—9:33a | None noticed |
| Freighter | | North | 9/30—9:43a | None noticed |
| Freighter | | North | 9/30—11:18a | None noticed[2] |
| Ship-barge/freighter? | | South | 9/30—12:02p | None noticed |
| Freighter | | North | 9/30—12:37p | None noticed |
| Freighter | | South | 9/30—3:17p | Near breaking, reflected waves and overtop @ 3 min after passage |
| Freighter | | North | 9/30—3:49p | Slight increase in wave chop |
| Freighter | | South | 9/30—4:05p | Slight increase in wave chop |
| Recreational boat | 15-18 ft | North | 10/1—8:47a | Boat wake interaction with exiting reflected waves at basin entrance |
| USCG vessel | 100 ft | South | 10/1—9:32a | Vessel wake and reflected waves interacted to cause breaking just inside basin |
| USCG vessel | 100 ft | South | 10/1—11:25a | None noticed, waves too choppy |
| Ship-barge pushed by tug | | North | 10/1—11:45a | None noticed, waves too choppy |
| Freighter | large | South | 10/1—12:07p | Interior wave breaking, trapped wave overtopping towards station |
| Freighter | 500 ft | South | 10/1—12:38p | None noticed, waves too choppy |
| Freighter | 200 ft | South | 10/1—12:43p | None noticed, waves too choppy |
| Freighter | | North | 10/1—1:16p | None noticed, waves too choppy |
| Ship-barge pushed by tug | | North | 10/1—2:20p | None noticed, waves too choppy |
| Recreation/work boat | | South | 10/1—2:49p | None noticed, waves too choppy |

[1] Inside boat basin.
[2] Waves not noticeable; while Detroit District vessel was moored near center of basin, strong currents pulled it toward the entrance when freighter bow was even with basin, and strong currents pushed Detroit District vessel away from entrance when freighter stern was even with basin.

worst in-basin wave activity. Unfortunately, neither 30 September nor 1 October were ideal to observe vessel-generated waves because easterly and northeasterly winds continuously generated short-period waves that distorted any vessel-generated waves.

# 4 Waves

The closest measured wave data to the project site is a National Oceanic and Atmospheric Administration buoy located over 121 km (75 miles) north of Port Huron in the central portion of the lake. Wind-generated hindcast wave data exist from the U.S. Army Engineer Wave Information Study (WIS). WIS Report 26 (Reinhard, Driver, and Hubertz 1991) provides hindcast wave data for stations along the entire shoreline of Lake Huron. WIS Report 26 is a 32-year hindcast (1956-1987) using wind fields during that time and transformation models to predict wave statistics at a given location. The closest WIS station to Port Huron is WIS Station Number 1 located approximately 8 km (5 miles) northeast of Port Huron. At this site, for the 32-year period of reporting, the calculated mean significant wave height was 0.8 m (2.6 ft) with a peak wave period of 4.0 sec. The most frequent direction band for waves was 202.5 deg (±11.25 deg) or waves propagating in a direction just 22.5 deg east of north.

An updated hindcast including more recent data was conducted to provide wave data closer to the project site. The summarized wave data that were used for modeling in the physical model and calculating sediment-transport potential are given in Table 2.

**Table 2**
**Updated Hindcast Wave Data**

| Wave Height m (ft) | Period, sec | Direction from, deg |
|---|---|---|
| 1.22 (4.0) | 6.0 | 11 |
| 2.07 (6.8) | 7.9 | 11 |
| 1.22 (4.0) | 5.0 | 59 |
| 1.86 (6.1) | 6.0 | 59 |

# 5 Sediment Transport

There are numerous sediment-transport relationships for calculating potential transport in the coastal zone. Some of these relationships are theoretically derived from energy that is expended by the water flow in transporting sediment. Others were developed from empirical measurements from laboratory experiments. Still others combine laboratory observations with theory to arrive at a transport potential.

The Port Huron study site is unique to the problem of calculating potential sediment transport, because it is influenced by open-coast breaking waves and strong unidirectional currents that imitate riverine transport. Therefore, three approaches to calculating potential sediment transport were considered: (a) steady-flow transport depending on a Shield's criterion approach for initiation of motion; (b) standard USACE breaking-wave transport potential approach as recommended in the USACE Engineer Manual (EM) 1110-2-1502 *Coastal Littoral Transport* (USACE 1992); and (c) a composite breaking wave-longshore current approach also described in USACE (1992).

The potential longshore sediment-transport rate depends on the quantity of material available for transport. Therefore, the term "potential" suggests that the calculated rate is the amount being transported if an unlimited supply of sediment were available. Lack of feeding sediments updrift of the area of interest and sediment trapping (from groins, jetties, harbors, navigation channels, etc.) all negatively impact the calculated rate. When any of these exist at a project site, the best approach to identify a more accurate transport rate is to conduct long-term shoreline change analysis, topographic and bathymetric surveys to examine rates of sediment trapping, and dredging-volume analysis.

## Steady-Flow Transport

Steady-flow sediment transport has been researched and studied for over 50 years. Most practical steady-flow transport formulas are based on experiments of total transport load. Sediment transport can occur as either bed load or suspended load, but differentiating between the two is not practical in an applied sense. Experimental data suggest that for relatively coarse materials (0.7 mm), suspended load contributes little to total transport (Nielsen 1992). At Port Huron, the dominance of coarse material suggests that suspended-sediment transport is a

minor component of the total load, so a total load formula comprised of bed-load developed theories should be appropriate.

Nielsen (1992) presents a modified form of the Meyer-Peter and Muller (1948) relationship for dimensionless transport that accounts for some consideration of "high stress" flows (i.e., flows that would tend to increase suspended sediment). Verification of the reasonable approximation of this modified formula should be directed to Nielsen (1992). Nielsen's (1992) relationship is:

$$\Phi = 12(\theta' - \theta_c)\sqrt{\theta'} \tag{1}$$

where

$\Phi$ = dimensionless sediment-transport rate

$\theta'$ = effective Shield's parameter

$\theta_c$ = critical Shield's parameter

Dimensionless bed-load transport, $\Phi_b$ is defined as:

$$\Phi_b = \frac{Q_b}{\sqrt{(s-1)gd^3}} \tag{2}$$

where

$\Phi_b$ = dimensionless bed-load transport

$Q_b$ = depth integrated bed-load transport, $L^2/T$

$s$ = specific gravity of sediment, $\rho_s/\rho_w$

$g$ = acceleration because of gravity

$d$ = $D_{50}$ grain size

Combining Equations 1 and 2 to solve for $Q_b$ (bed load per unit width) gives:

$$Q_b = 12(\theta' - \theta_c)\sqrt{\theta'}\sqrt{(s-1)gd^3} \tag{3}$$

The Shield's parameter is a descriptor of the initiation of sediment motion. In Shield's original work, laboratory experiments were used to measure velocities and calculate bottom shear stress for flows that caused movement in various sediments. The famous Shield's curve was created defining the critical bottom shear stress causing sediment movement. Shield's original work however is awkward for practical application because it involves a cumbersome iteration to determine the Shield's parameter for a given flow condition and sediment type. Madsen and Grant (1976) modified the Shield's parameter so that the curve more clearly represents a relationship between fluid flows and sediment characteristics, thus avoiding the iterative process.

The ADCP current data collected during the fall 1997 field-data collection effort at Port Huron was reduced to extract the near-bottom fluid velocity vectors. Proximal vectors for the multiple transect runs and/or days of collected data were averaged to obtain a representative vector field for each transect. Each resulting flow vector was used to calculate a Shield's parameter that then was compared with a critical Shield's parameter for a set of representative sediments. If the Shield's parameter exceeded the critical Shield's parameter for that sediment size, then transport occurred and Equation 3 was used to calculate a unit-transport rate. This unit-transport rate was converted to a total-transport rate by assuming the flow vectors described above occurred across a given length defined as the distance between the midpoints of two vectors.

The characteristic sediments used in computing transport potential were chosen to represent the sediment population of the study area (Figure 13). These sediments (listed in Table 3) are those that were found inside or along the entrance to the boat basin and identified as being available for transport.

The unidirectional transport rates calculated as described above are represented in Figure 14. Comparing Figure 14 with the velocity vectors from Figures 10 and 11 shows the correlation of sediment transport to bottom velocity. Figure 14, however, indicates that the majority of transport occurs south of the boat basin where the currents are strongest. Even for the finest sediment (BB4, $D_{50} = 0.17$ mm), little transport potential exists to the north of the basin. This suggests that the unidirectional flow alone is not sufficient to transport significant quantities of sediment from the north to fill in the boat basin. Anecdotal evidence supports this conclusion during calm wave days when the unidirectional currents remain strong, yet water clarity indicates little if any material is in suspension.

**Table 3**
**Representative Sediments from Inside and Near Boat Basin**

| Location[1] | $D_{50}$ grain size, mm |
|---|---|
| BB1 | 0.21 |
| BB2 | 9.7 |
| BB3 | 15.0 |
| BB4 | 0.17 |
| CL1 | 0.62 |
| CL2 | 19.0 |
| CL3 | 25.5 |
| CL4 | 20.0 |
| CL5 | 8.9 |
| CL6 | 40.0 |

[1]BB nos. are samples taken within the boat basin; CL nos. are samples taken along the center line of the boat basin entrance.

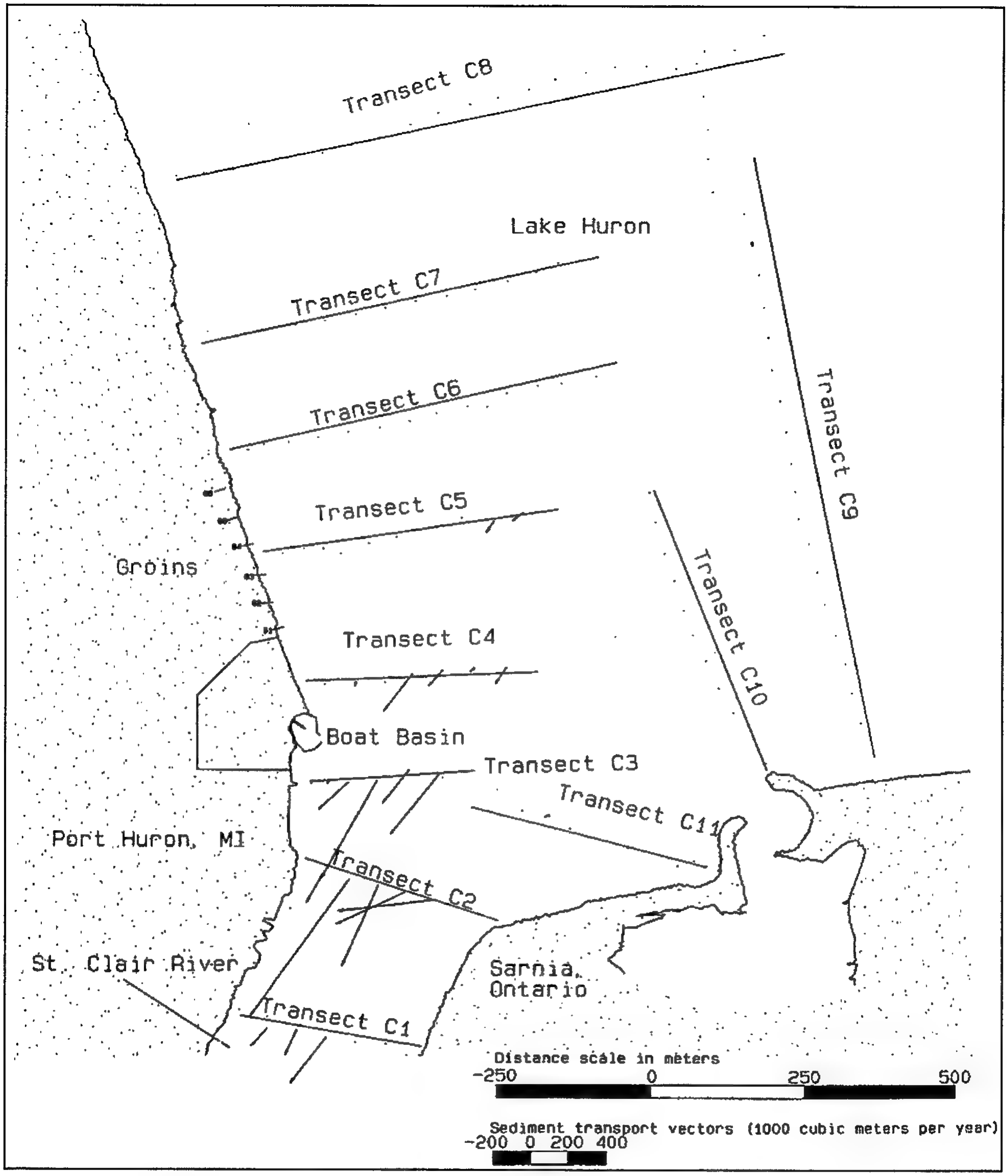



Figure 14. Unidirectional sediment-transport vectors

## Waves-Only Transport

For wave-only transport, wave-energy flux or power is used. Wave energy is proportional to the square of breaking-wave height. When including the effects of the group velocity, the volume-transport rate depends on breaking-wave height to the 5/2 power. At Port Huron, the wave hindcast data were used from the offshore location and transformed inshore to breaking using a Snell's Law approach. Longshore-transport rate also depends on the sine of two times the breaking wave angle, also determined from the Snell's law transformation approach. Equation 4 is modified from Equation 6-7b in USACE (1992) for 0.78 breaking criterion, converting wave height from root-mean-square to significant and for fresh water rather than salt water.

$$Q_1 = \left(6.446 \times 10^3\right) H_{br}^{5/2} \sin\left(2\alpha_{br}\right) \tag{4}$$

where

$Q_l$ = volumetric sediment-transport rate, m$^3$/day

$H_{br}$ = breaking wave height

$\alpha_{br}$ = breaking wave angle

Table 4 summarizes transport for waves from each direction (as a percent occurrence) obtained from summary tables in Reinhard, Driver, and Hubertz (1991). The ±17.5 percent uncertainty calculation is based on the uncertainty of each component of Equation 4. Assuming ±5 percent uncertainty for wave height and direction, respectively, translates into a ±17.5 percent uncertainty for $Q_l$ (Kraus and Rosati 1998).

**Table 4**
**Waves-Only Potential Sediment-Transport Rates**

| *H* m | *T* sec | % | Dir, deg | $H_b$, m | $Dir_b$, deg | $Q_l$, m$^3$/year | ±17.5% m$^3$/year |
|---|---|---|---|---|---|---|---|
| 0.61 | 4 | 15.2 | 11 | 1.07 | 16.5 | 230,000 | 40,300 |
| 1.22 | 6 | 2.88 | 11 | 2.19 | 15.7 | 250,000 | 43,700 |
| 2.07 | 7.9 | 0.863 | 11 | 3.73 | 15.6 | 282,000 | 49,400 |
| 2.62 | 8.6 | 0.657 | 11 | 4.66 | 16.0 | 385,000 | 67,400 |
| 3.02 | 9.2 | 0.088 | 11 | 5.36 | 16.1 | 72,900 | 12,800 |
| 0.61 | 4 | 13.4 | 59 | 0.63 | 26.1 | 79,300 | 13,900 |
| 1.22 | 5 | 4.26 | 59 | 1.21 | 29.2 | 138,000 | 24,200 |
| 1.86 | 6 | 0.922 | 59 | 1.83 | 30.0 | 85,300 | 14,900 |
| 2.35 | 6.5 | 1.10 | 59 | 2.29 | 31.0 | 180,000 | 31,500 |
| 2.68 | 7 | 0.213 | 59 | 2.62 | 30.8 | 48,800 | 8,540 |
| | | | | | Total | 1,751,300 | 306,640 |

## Waves and Current Transport

A more likely mechanism for sediment transport at Port Huron is from the combined effect of waves and currents. As noted from the current-only calculations above for the representative sediments, though the currents are strong at Port Huron, they do not appear to be moving sediments independently of other hydrodynamic forces. Breaking waves probably destabilize sediments making them available for transport as suspended or bed load by the unidirectional currents that transport the sediments southward along the beach. USACE (1992) documents early work from Grant (1943) that stated nearshore transport results from the combined effects of waves and currents—waves placing the sand in motion and currents producing a net sand advection. Inman and Bagnold (1963) developed the formulation for longshore transport on beaches resulting from the combination of breaking waves and longshore currents. This relationship, which was modified from Equation 6-15b in USACE (1992) for use in this study for 0.78 breaking criterion, converting wave height from root-mean-square to significant and for fresh water rather than salt water, is given in Equation 5.

$$Q_1 = 3.329 \times 10^3 H_{br}^{5/2} V_1 \tag{5}$$

where

$Q_l$ = volumetric sediment-transport rate, m$^3$/day

$H_{br}$ = breaking-wave height

$V_l$ = longshore current

The longshore current value used in Equation 5 was taken as the most near-shore depth-averaged current measured with the ADCP from the transects north of the boat basin—namely, Transects C4, C5, C6, C7, and C8. Table 4 summarizes the currents and transport rates calculated by Equation 5. Wave data used in Equation 5 for each case are identical to that presented in Table 4, so only breaking height and period are repeated for reference in Table 5. Similar uncertainty estimates are made on the calculation of $Q_l$ in Equation 5. Plus/minus 5 percent for wave height and $\pm 10$ percent for current velocity translates into a $\pm 20$ percent uncertainty for $Q_l$.

These rates appear to be reasonable approximations of a likely potential longshore sediment-transport rate. Considering the limited supply of sediment to the north and the presence of sediment-trapping structures, an actual longshore-transport rate on the order of 100,000 m$^3$/year ($\pm$50,000 m$^3$/year) is probably appropriate. It should be noted that this estimate should be considered now preliminary, as it is not supported by any field data (measured sediment transport or historic bathymetric and topographic surveys for trapping rates).

| Table 5<br>Waves and Current Potential Sediment-Transport Rates | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Transect C4 | | Transect C5 | | Transect C6 | | Transect C7 | | Transect C8 | |
| $H_{br}$ m | $T$ s | $Q_l$ m$^3$/year | ±20 m$^3$/year | $Q_l$ m$^3$/year | ±20 m$^3$/year | $Q_l$ m$^3$/year | ±20 m$^3$/year | $Q_l$ m$^3$/year | ±20 m$^3$/year | $Q_l$ m$^3$/year | ±20 m$^3$/year |
| 1.07 | 4 | 51,500 | 10,300 | 70,900 | 14,200 | 40,600 | 8,120 | 58,000 | 11,600 | 43,200 | 8,630 |
| 2.19 | 6 | 40,800 | 8,160 | 56,100 | 11,200 | 32,100 | 6,430 | 45,900 | 9,180 | 34,200 | 6,840 |
| 3.73 | 7.9 | 35,600 | 7,120 | 48,900 | 9,790 | 28,000 | 5,610 | 40,000 | 8,010 | 29,800 | 5,960 |
| 4.66 | 8.6 | 42,400 | 8,470 | 58,200 | 11,600 | 33,400 | 6,670 | 47,600 | 9,530 | 35,500 | 7,090 |
| 5.36 | 9.2 | 7,470 | 1,490 | 10,300 | 2,050 | 5,880 | 1,180 | 8,400 | 1,680 | 6,250 | 1,250 |
| 0.63 | 4 | 15,900 | 3,180 | 21,800 | 4,370 | 12,500 | 2,500 | 17,900 | 3,570 | 13,300 | 2,660 |
| 1.21 | 5 | 18,600 | 3,710 | 25,500 | 5,110 | 14,600 | 2,920 | 20,900 | 4,180 | 15,500 | 3,110 |
| 1.83 | 6 | 9,170 | 1,840 | 12,600 | 2,520 | 7,220 | 1,450 | 10,300 | 2,060 | 7,680 | 1,540 |
| 2.29 | 6.5 | 17,000 | 3,400 | 23,400 | 4,680 | 13,400 | 2,680 | 19,100 | 3,830 | 14,200 | 2,850 |
| 2.62 | 7 | 4,320 | 864 | 5,940 | 1,190 | 3,400 | 680 | 4,860 | 972 | 3,620 | 724 |
| | | 242,760 | 48,534 | 333,640 | 66,710 | 191,100 | 38,240 | 272,960 | 54,612 | 203,250 | 40,654 |

## Historic Records

Historic shoaling and dredging information from USCG records provide some limited data on sediment transport at Port Huron. In 1978, the Detroit District submitted a letter to the USCG stating that sediment transport at Port Huron was expected to be similar to that at Port Sanilac 48 km (30 miles) to the north. Studies at Port Sanilac indicated that net transport was to the south at 23,000 cu m/year (30,000 cu yd/year). Shoaling in Port Sanilac Harbor was 2,300 to 4,600 cu m/ year (3,000 to 6,000 cu yd/year). Geographically, there are few hydraulic (and thus sediment-transport potential) similarities between Port Sanilac and Port Huron. Port Sanilac is far enough north that it is beyond the influence of Lake Huron discharge into the St. Clair River. Though the wave climates may be similar at the two locations, Port Huron is so far south in Lake Huron that wave approaches are more narrowly bounded from the north to northeast directions. In addition, the boat basin at Port Huron is located at a critical shoreline orientation change—shores south of the boat basin run along an azimuth of approximately 205 deg (along the direction of the St. Clair River), while shores north of the boat basin (including Port Sanilac) run approximately 160 deg. This critical orientation change this far south in Lake Huron will have significant impacts on wave propagation direction and sediment transport relative to the shoreline.

Limited information from dredging records at the boat basin provides little insight into shoaling and transport rates. Reliance on these data must be viewed with skepticism because previous boat basin configurations doubtless influenced the amount of sedimentation—encouraging deposition in some cases or discouraging it in others. In addition, there is no way to know what dredging volumes are "maintenance" dredging, i.e., removal of material that has

accumulated since a previous dredging cycle, versus “new work” or the length of time between dredging cycles to associate a period of time for any shoaled material. Also, once a shoal is “full,” additional sediment will typically bypass the shoaling area without adding volume. Therefore, USCG permit requests to the Detroit District in the mid- to late 1990s for dredging volumes ranging from 2,500 to 5,000 cu m (3,300 to 6,700 cu yd) cannot be used with any degree of confidence for estimating transport rates.

# 6 Physical Model

## Model

### Design of model

The Port Huron Harbor model (Figure 15) was constructed to an undistorted linear scale of 1:60, model to prototype. Scale selection was based on the following factors:

*a.* Depth of water required in the model to prevent excessive bottom friction.

*b.* Absolute size of model waves.

*c.* Available shelter dimensions and area required for model construction.

*d.* Efficiency of model operation.

*e.* Available wave-generating and wave-measuring equipment.

*f.* Model construction costs.

A geometrically undistorted model was necessary to ensure accurate reproduction of wave and current patterns. Following selection of the linear scale, the model was designed and operated in accordance with Froude's model law (Stevens et al. 1942). The scale relations used for design and operation of the model were as follows:

| Characteristic | Dimension[1] | Model-Prototype Scale Relations |
|---|---|---|
| Length | $L$ | $L_r = 1:60$ |
| Area | $L^2$ | $A_r = L_r^2 = 1:3,600$ |
| Volume | $L^3$ | $V_r = L_r^3 = 1:216,000$ |
| Time | $T$ | $T_r = L_r^{\bullet} = 1:7.75$ |
| Velocity | $L/T$ | $V_r = L_r^{\bullet} = 1:7.75$ |
| Discharge | $L^3/T$ | $Q_r = L_r^{5/2} = 1:27,871$ |

[1] Dimensions are in terms of length (L) and time (T).

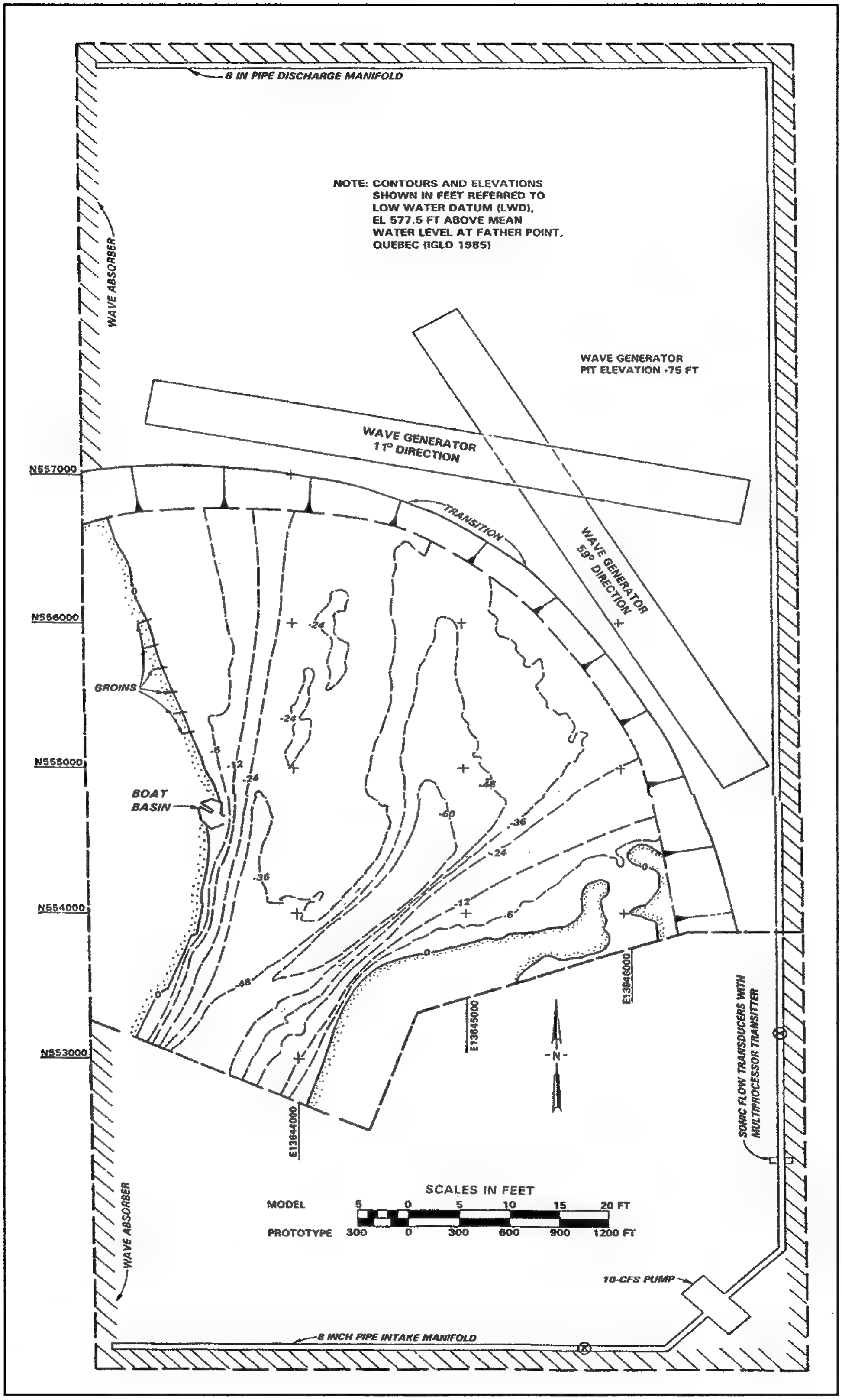



Figure 15. Model layout

Stone absorber has been installed adjacent to the existing Port Huron Harbor breakwater and, in addition, was used for some of the proposed improvement plans. Based on past experience, 1:60-scale model structures should not create sufficient scale effects to warrant geometric distortion of stone sizes in order to ensure proper transmission and reflection of wave energy. Therefore, rock-size selection was based on linear scale relations and an assumed specific weight of 2,643 kgcm (165 pcf) for the prototype rock.

Ideally, a quantitative, three-dimensional, movable-bed model investigation would best determine the impacts of breakwater modifications with regard to sediment deposition in the vicinity of the harbor. However, this type of model investigation is difficult and expensive to conduct, and each area in which such an investigation is contemplated must be carefully analyzed. In view of the complexities involved in conducting movable-bed model studies and because of limited funds and time for the Port Huron Harbor project, the model was molded in cement mortar (fixed-bed), and a tracer material was obtained to qualitatively determine sediment patterns and subsequent deposits in the harbor vicinity.

### Model and appurtenances

The model was constructed of concrete mortar and reproduced the extreme southern portion of Lake Huron and the entrance to the St. Clair River. Approximately 1.1 km (0.7 miles) of the United States shoreline was reproduced on the west, which included Port Huron Harbor, as well as about 0.8 km (0.5 miles) of the Canadian shoreline on the east. Detailed bathymetry was reproduced in Lake Huron with a sloping transition to the wave generator pit elevation of -23 m (-75 ft). The total area reproduced in the model was approximately 965 sq m (10,400 sq ft), representing about 3.4 sq km (1.3 square miles) in the prototype. Vertical control for model construction was based on low water datum (lwd), and horizontal control was referenced to a local prototype grid system. A general view of the model is shown in Figure 16.

Model waves were reproduced by an 18.3-m-long (60-ft-long), electro-hydraulic, unidirectional spectral wave generator with a trapezoidal-shaped, vertical motion plunger. The wave generator utilized a hydraulic power supply. The vertical motion of the plunger was controlled by a computer-generated command signal, and movement of the plunger caused a displacement of water that generated the required experimental waves. The wave generator also was mounted on retractable casters, which enabled it to be positioned to generate waves from the required directions.

An Automated Data Acquisition and Control System, designed and constructed at WES (Figure 17), was used to generate and transmit wave-generator control signals, monitor wave-generator feedback, and secure and analyze wave data at selected locations in the model. Through the use of a microvax computer, the electrical output of parallel-wire, capacitance-type wave gauges, which varied with the change in water-surface elevation with respect to time, were recorded on magnetic disks. These data then were analyzed to obtain the parametric wave data.

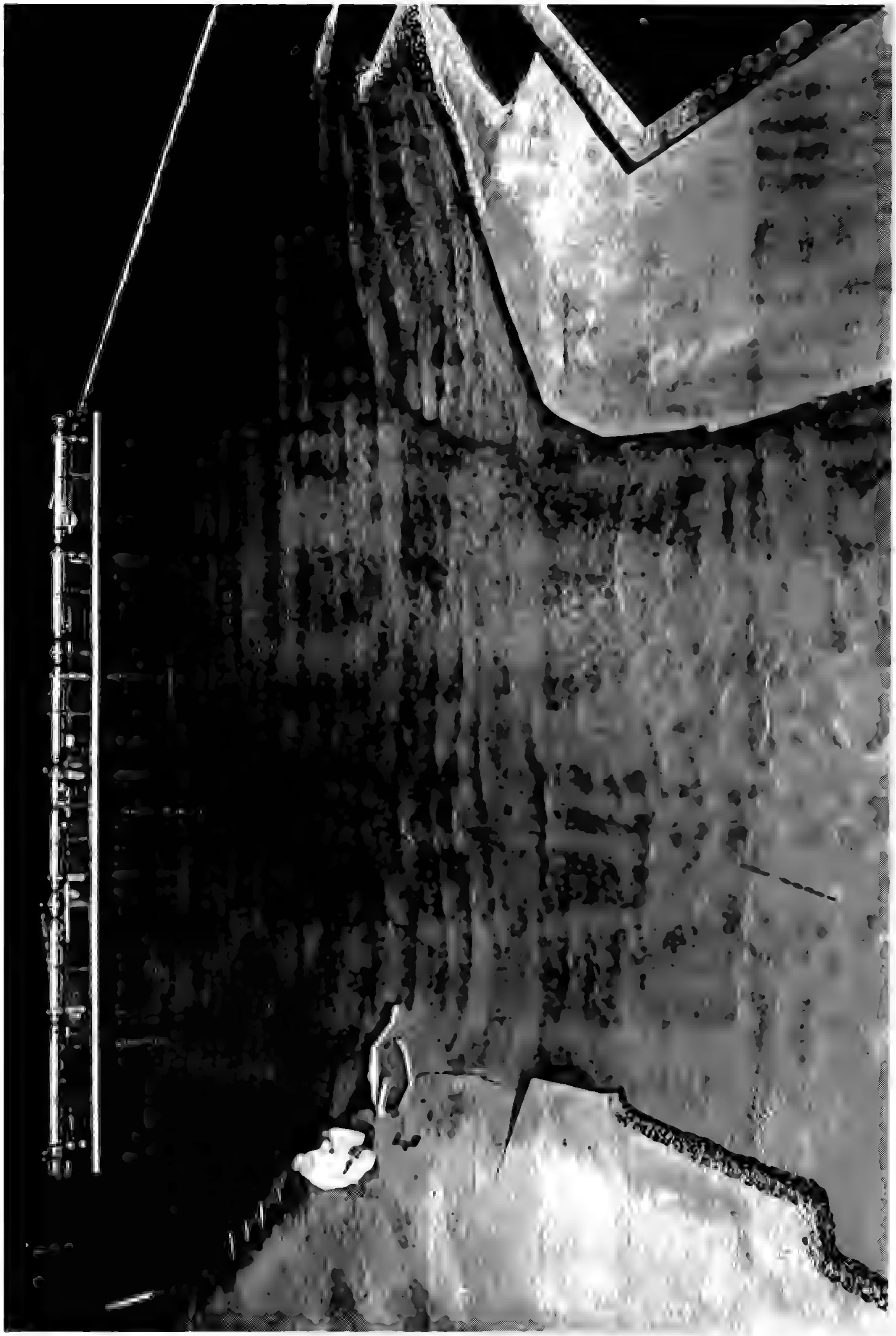


Figure 16. General view of model

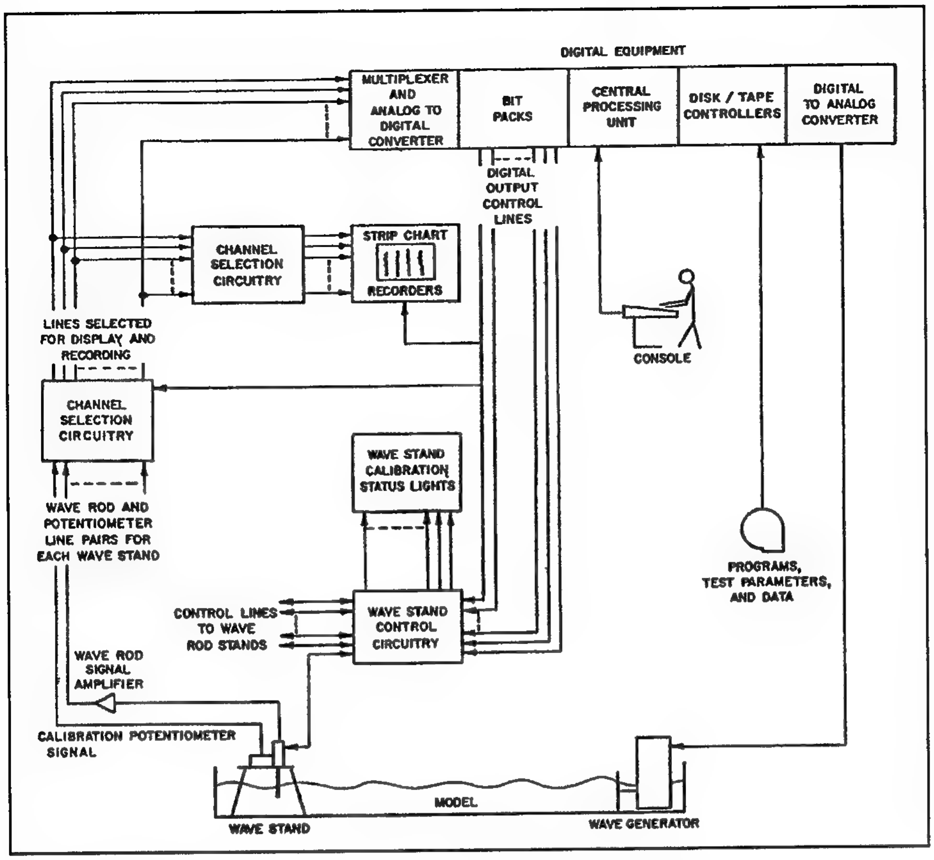



Figure 17. Automated Data Acquisition and Control System

A water circulation system (Figure 15), consisting of a 20.3-cm (8-in.), perforated-pipe water-intake manifold, a 0.28-cms (10-cfs) pump, and sonic flow transducers with a multiprocessor transmitter, was used in the model to reproduce steady-state flows through the St. Clair River that corresponded to selected prototype flows. The magnitudes of these currents were measured by timing the progress of weighted floats over known distances.

A 0.6-m (2-ft) (horizontal) solid layer of fiber wave absorber was placed along the inside perimeter of the model to dampen wave energy that might otherwise be reflected from the model walls. In addition, guide vanes were placed along the wave generator sides in the flat pit area to ensure proper formation of the wave train incident to the model contours.

### Design of tracer material

As discussed previously, a fixed-bed model was constructed and a tracer material selected to qualitatively determine movement and deposition of sediment in the vicinity of the harbor. Tracer was chosen in accordance with the scaling relations of Noda (1972), which indicate a relation, or model law, among the four basic scale ratios, i.e., the horizontal scale, $\lambda$ ; the vertical scale, $\mu$ ; the sediment size ratio, $\eta_D$ ; and the relative specific weight ratio, $\eta_{\cdot}$. These relations were

determined experimentally using a wide range of wave conditions and bottom materials and are valid mainly for the breaker zone.

Noda's scaling relations indicate that movable-bed models with scales in the vicinity of 1:60 (model to prototype) should be distorted (i.e., they should have different horizontal and vertical scales). Since the fixed-bed model of Port Huron Harbor was undistorted to allow accurate reproduction of short-period wave and current patterns, the following procedure (which has been successfully used and validated for undistorted models) was used to select a tracer material. Using the prototype sand characteristics (median diameter, $D_{50}$ = 0.17-0.90 mm, specific gravity = 2.65) and assuming the horizontal scale to be in similitude (i.e., 1:60), the median diameter for a given vertical scale was then assumed to be in similitude and the tracer median diameter and horizontal scale were computed. This resulted in a range of tracer sizes for given specific gravities that could be used. Although several types of movable-bed tracer materials were available at WES, previous investigations (Giles and Chatham 1974; Bottin and Chatham 1975) indicated that crushed coal tracer more nearly represented the movement of prototype sand. Therefore, quantities of crushed coal (specific gravity = 1.30; median diameter, $D_{50}$ = 0.42-2.89 mm) were selected for use as a tracer material throughout the model investigation.

## Experimental Conditions and Procedures

### Selection of experimental conditions

**Still-water levels.** Still-water levels (swls) for wave action models are selected so that various wave-induced phenomena that are dependent on water depths are accurately reproduced in the model. These phenomena include refraction of waves in the project area, overtopping of harbor structures by waves, reflection of wave energy from various structures, and transmission of wave energy through porous structures.

Water levels on the Great Lakes vary from year to year and from month to month. Also, at any given location, the water level can vary from day to day and hour to hour. Great Lakes' water level data for the period 1918-1996 indicate that higher water levels usually occur during the spring and early summer and lower water levels occur during the winter months. For Lake Huron, the minimum and maximum lake levels generally occur in February and July, respectively. During the period of record, the average lake level for Lake Huron was +0.58 m (+1.9 ft). The highest level was +1.6 m (+5.5 ft) in October 1986, and the lowest level was -0.2 m (-0.7 ft) in March 1994. The seasonal variation in the mean monthly level of Lake Huron usually ranges from 0.21 m (0.7 ft) to 0.6 m (2.0 ft), with an average variation of 0.4 m (1.3 ft).

Seasonal and longer variations in the levels of the Great Lakes are caused by variations in precipitation and other factors that affect the actual quantities of water in the lakes. Wind tides and seiches are relatively short-period fluctuations caused by the tractive force of wind blowing over the water surface and by

differential barometric pressures and are superimposed on the longer period variations in the lake level. Large short-period rises in local water levels are associated with the most severe storms, which generally occur in the winter when the lake level is usually low; therefore, the probability that a high lake level and a large wind tide or seiche will occur simultaneously is relatively small.

Lake levels of +0.52 and +1.07 m (+1.7 and +3.5 ft) were selected by the Detroit District for use during the model experiments. The lower value (+0.52 m (+1.7 ft)) represents the long-term summer (April-October) average for the period of record. The higher value (+1.07 m (+3.5 ft)) represents the summer average for Lake Huron during 1997, when the lake levels were unusually high.

**Factors influencing selection of experimental wave characteristics.** In planning the experimental program for a model investigation of harbor wave-action problems, it is necessary to select heights, periods, and directions for the experimental waves that will allow a realistic study of the proposed improvement plans and an accurate evaluation of the elements of the various proposals. Surface-wind waves are generated primarily by the interactions between tangential stresses of wind flowing over water, resonance between the water surface and atmospheric turbulence, and interactions between individual wave components. The height and period of the maximum significant wave that can be generated by a given storm depend on the wind speed, the length of time that wind of a given speed continues to blow, and the distance over water (fetch) that the wind blows. Selection of experimental wave conditions entails evaluation of such factors as follows:

*a.* Fetch and decay distances (the latter being the distance over which waves travel after leaving the generating area) for various directions from which waves can approach the problem area.

*b.* Frequency of occurrence and duration of storm winds from the different directions.

*c.* Alignment, size, and relative geographic position of the navigation structures.

*d.* Alignments, lengths, and locations of the various reflecting surfaces in the area.

*e.* Refraction of waves caused by differentials in depth in the area lakeward of the site, which may create either a concentration or a diffusion of wave energy.

**Deepwater wave data.** Measured prototype wave data covering a sufficiently long duration from which to base a comprehensive statistical analysis of wave conditions were unavailable for the Port Huron area. However, statistical wave hindcast estimates representative of this area were available from Resio and Vincent (1977). This hindcast was developed for 28 points along the U.S. Lake Huron shore using historical wind data from three climatological stations. Significant wave heights and peak wave periods were calculated for 5, 10, 20, 50, and 100 years for three wave approach angles to shore.

This hindcast study was updated by Reinhard, Driver, and Hubertz (1991). In the updated report, 32 years (1956-1987) of hindcast wind and wave information are summarized for locations along the U.S. shoreline of Lake Huron in four data products: percent occurrence tables, wave rose diagrams, mean and largest wave heights, and 32-year statistics tables and return period tables. The complete hindcast is available at 3-hr intervals for the period of record. Deepwater wave hindcast data for the Port Huron model were obtained at Sta 1 (Figure 18).

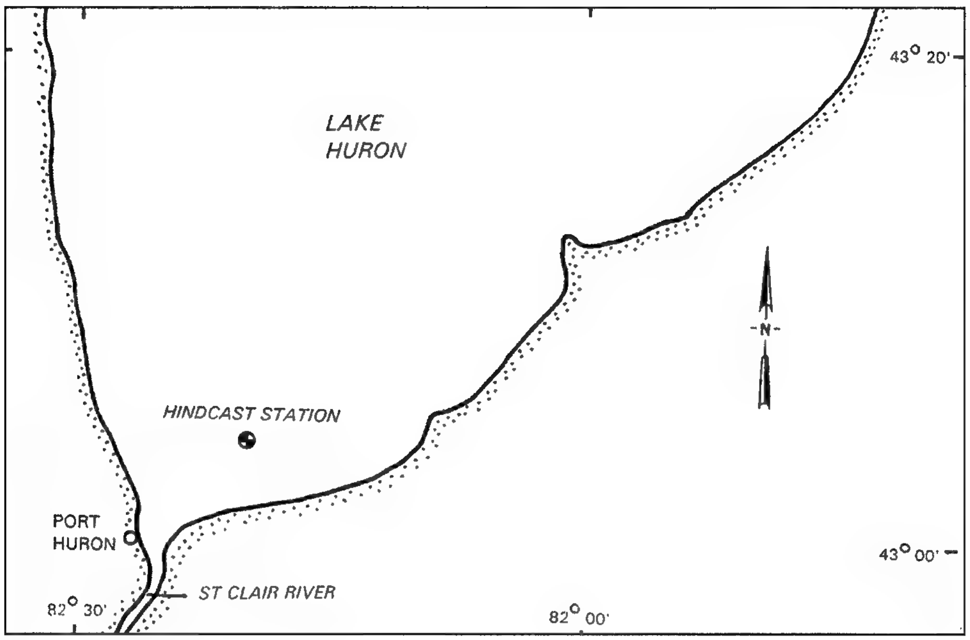



Figure 18. Location of wave hindcast station

**Wave transformation.** When waves move into water of gradually decreasing depth, transformations take place in all wave characteristics except wave period (to the first order of approximation). The most important transformations with respect to selection of experimental wave characteristics are the changes in wave height and direction of travel because of the phenomenon referred to as wave refraction. When the refraction coefficient $K_r$ is determined, it is multiplied by the shoaling coefficient $K_s$ and gives a conversion factor for deepwater wave heights to shallow-water values. The shoaling coefficient, a function of wave length and water depth, can be obtained from the Shore Protection Manual (1984).

For this study, deepwater wave data were converted to shallow-water values through the use of a wave-transformation model. The transformation model included refractive, diffractive, and shoaling effects of the offshore bathymetry. Wave characteristics were transformed from the wave hindcast station (Figure 18) to the approximate location of the wave generator in the model using the computer program WAVETRAN (Jensen 1983). The program is based upon the TMA

(Texel-MARSEN-ARSLOE) spectral transformation of waves, with no additional energy input from wind, and straight and parallel bottom contours. Wave sheltering from nearby land masses and shoals also can be determined.

Deepwater wave hindcast data from two angle classes were considered for transformation to shallow-water values at Port Huron. Angle class 1 consisted of waves approaching from 348.5 to 33.5 deg, and angle class 2 entailed waves approaching from 33.5 to 78.5 deg. Results indicated that waves from angle class 1 were, by far, predominant. Approximately 91 percent of the wave occurrences were noted in angle class 1. Waves from 11 deg and 59 deg were determined to be representative of angle classes 1 and 2, respectively.

**Selection of experimental waves.** Based on the transformation of hindcast data from Sta 1, the following conditions were selected as representative of waves lakeward of Port Huron (approximate location of wave generator in model) during boating season and for the entire year.

| Navigation Season (Apr-Oct) | | All Year | |
|---|---|---|---|
| Return Period, year | Wave Length, m (ft) | Return Period, year | Wave Height, m (ft) |
| 11 Deg | | | |
| 2 | 2.07 (6.8) | 2 | 2.13 (7.0) |
| 5 | 2.29 (7.5) | 5 | 2.29 (7.5) |
| 10 | 2.47 (8.1) | 10 | 2.53 (8.3) |
| 20 | 2.62 (8.6) | 20 | 2.68 (8.8) |
| 25 | 2.68 (8.8) | 25 | 2.74 (9.0) |
| 50 | 2.83 (9.3) | 50 | 2.93 (9.6) |
| 100 | 3.02 (9.9) | 100 | 3.08 (10.1) |
| 59 Deg | | | |
| 2 | 1.86 (6.1) | 2 | 1.92 (6.3) |
| 5 | 2.04 (6.7) | 5 | 2.10 (6.9) |
| 10 | 2.19 (7.2) | 10 | 2.26 (7.4) |
| 20 | 2.35 (7.7) | 20 | 2.41 (7.9) |
| 25 | 2.41 (7.9) | 25 | 2.47 (8.1) |
| 50 | 2.56 (8.4) | 50 | 2.62 (8.6) |
| 100 | 2.68 (8.8) | 100 | 2.77 (9.1) |

Since the Port Huron marina is used only during boating season, wave heights associated with 2-, 20-, and 100-year return periods during navigation season were selected for model experiments. Wave periods associated with these wave heights (based on the hindcast) were used as shown in the following tabulation. Note also that smaller wave conditions were selected to represent more normal occurrences (those with less than a 2-year return period).

| Selected Port Huron Experimental Wave Conditions | |
|---|---|
| **11 Deg** | **59 Deg** |
| 4-sec, 0.61-m (2-ft) | 4-sec, 0.61-m (2-ft) |
| 6-sec, 1.22-m (4-ft) | 5-sec, 1.22-m (4-ft) |
| 7.9-sec, 2.07-m (6.8-ft) | 6-sec, 1.86-m (6.1-ft) |
| 8.6-sec, 2.62-m (8.6-ft) | 6.5-sec, 2.35-m (7.7-ft) |
| 9.2-sec, 3.02-m (9.9-ft) | 7-sec, 2.68-m (8.8-ft) |

Unidirectional wave spectra were generated based on TMA parameters for the selected waves and used throughout the model investigation. Plots of a typical wave spectra are shown in Figure 19. The dashed line represents the desired spectra, while the solid line represents the spectra reproduced in the model. A generic TMA gamma function of 3.3 was used to determine the spread of the spectra. The larger the gamma value, the sharper the peak in the energy-distribution curve. A typical wave train time series is shown in Figure 20, which depicts water-surface elevation versus time. Selected waves were defined by significant wave height, the average height of the highest one-third of the waves or $H_s$. In deepwater, $H_s$ is very similar to $H_{mo}$ (energy-based wave) where $H_{mo} = 4 (E)^{1/2}$, and $E$ equals total energy in the spectra, which is obtained by integrating the energy density spectra over the frequency range.

**Riverflows.** The St. Clair River flows southerly from Lake Huron to Lake St. Clair. Based on the prototype data obtained during September 1997, riverflow magnitudes in the St. Clair River were 2.1 mps (6.9 fps) immediately inside the river mouth north of the bridge to Canada. These river current magnitudes were reproduced in the model and used during model experiments with flow conditions.

## Analysis of model data

Relative merits of the various improvement plans were evaluated by the following:

*a.* Comparison of wave heights at selected locations in the model.

*b.* Comparison of wave-induced current patterns and magnitudes.

*c.* Comparison of sediment-tracer movement and subsequent deposits.

*d.* Visual observations and wave-pattern photographs.

In the wave-height data analysis, the average height of the highest one-third of the waves ($H_s$), recorded at each gauge location, was computed. All wave heights

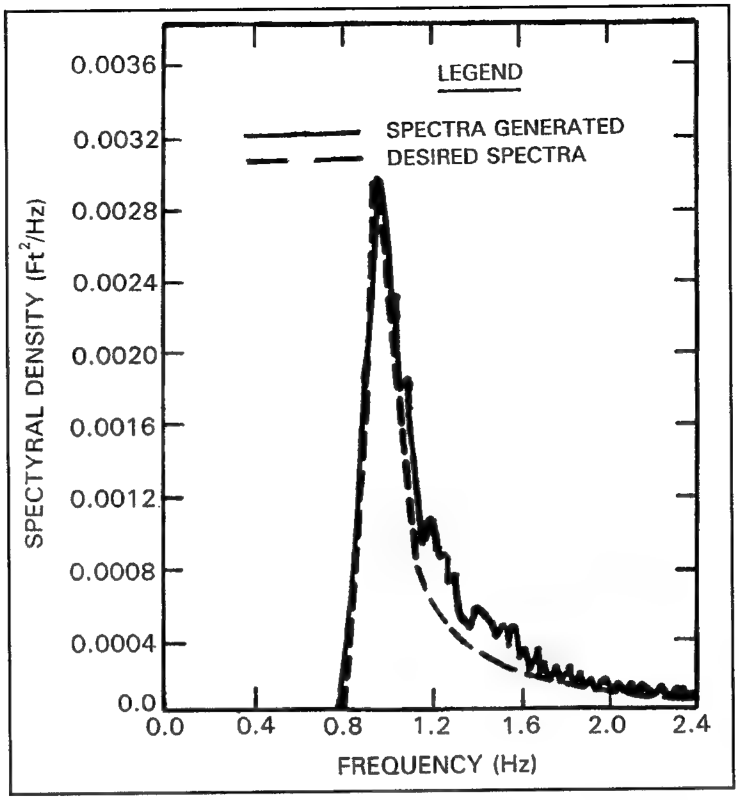



Figure 19. Typical energy density versus frequency plots (model terms) for a wave spectra; 7.9-sec, 2.07-m (6.8-ft) waves (prototype)

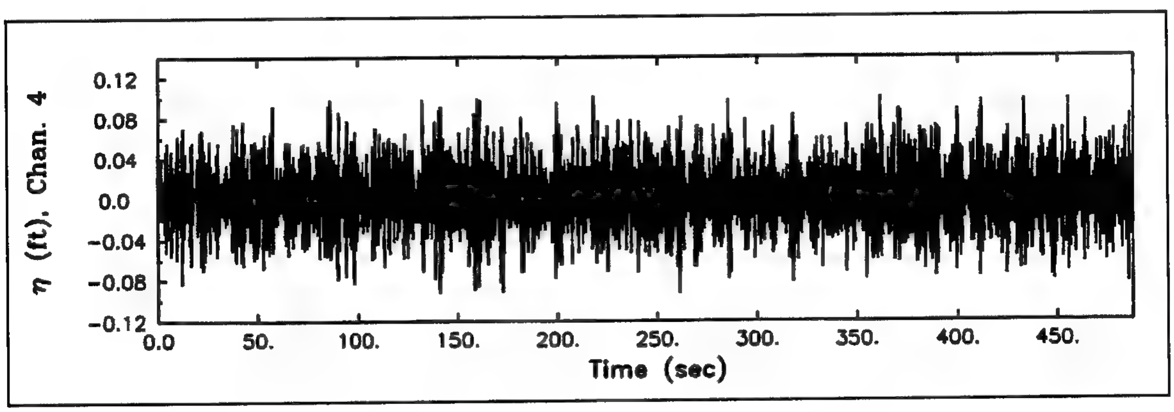



Figure 20. Typical model-scale wave train time series; 7.9-sec, 2.07-m (6.8-ft) waves (prototype)

then were adjusted by application of Keulegan's equation[1] to compensate for excessive model wave height attenuation because of viscous bottom friction. From this equation, reduction of model wave heights (relative to the prototype) can be calculated as a function of water depth, width of wave front, wave period,

[1] Keulegan, G. H. (1950). "The Gradual Damping of a Progressive Oscillatory Wave with Distance in a Prismatic Rectangular Channel," Unpublished data, National Bureau of Standards, Washington, DC, prepared at request of Director, WES, Vicksburg, MS, by Letter of 2 May 1950.

water viscosity, and distance of wave travel, and the model data can be corrected and converted to their prototype equivalents.

# Experiments and Results

## Experiments

**Existing conditions.** Comprehensive wave-height experiments were conducted for existing conditions (Plate 1) to establish a base from which to evaluate the effectiveness of the various improvement plans. Wave-height data were secured at various locations in the existing marina. In addition, wave-induced current patterns and magnitudes, sediment-tracer experiments, and wave-pattern photographs were obtained for representative wave conditions. Wave heights in the marina also were measured as a result of wakes from various vessels navigating the St. Clair River.

**Improvement plans.** Wave-height experiments were obtained for 16 plan configurations. In general, variations consisted of changes in the lengths, alignments, or elevation of the breakwaters and/or the installation of stone adjacent to the existing structures. Sediment-tracer patterns and subsequent deposits, wave-induced current patterns and magnitudes, wave-pattern photographs, and vessel-wake experiments were obtained for some of the improvement plans. Brief descriptions of the improvement plans are presented in the following subparagraphs; dimensional details are shown in Plates 2-10.

*a.* Plan 1 (Plate 2) consisted of the installation of a 12.2-m (40-ft) sheet-pile extension of the outer north breakwater along its original alignment. The breakwater extension was constructed of Plexiglas at the elevation of the existing structure (+2.1 m (+7.0 ft) LWD).

*b.* Plan 2 (Plate 2) included the installation of an 18.3-m (60-ft) sheet-pile extension of the outer north breakwater along its original alignment.

*c.* Plan 3 (Plate 2) entailed the installation of a 24.4-m (80-ft) sheet-pile extension of the outer north breakwater along its original alignment.

*d.* Plan 4 (Plate 3) involved the 24.4-m (80-ft) sheet-pile extension of Plan 3. In addition, a 24.4-m-long (80-ft-long) stone absorber was installed along the portion of the north breakwater with the north-south alignment on its lakeward side. The absorber consisted of 9,070-kg (10-ton) stone with an el of +2.13 m (+7.0 ft) and was placed on a 1V:1.5H slope.

*e.* Plan 5 (Plate 4) consisted of a 39.6-m-long (130-ft-long) sheet-pile breakwater that was attached to the existing breakwater at the northeast corner of the harbor and extended southeasterly terminating at the same point as the Plan 1 structure extension. The existing north breakwater was left in place.

*f.* Plan 6 (Plate 4) involved the elements of Plan 5 with a 6.1-m (20-ft) sheet-pile extension that terminated at the same point as the Plan 2 structure extension.

*g.* Plan 7 (Plate 4) entailed the elements of Plan 5 with a 12.2-m (40-ft) sheet-pile extension that terminated at the same point as the Plan 3 structure extension.

*h.* Plan 8 (Plate 5) consisted of a 33.5-m-long (110-ft-long) southerly dogleg extension of the north breakwater.

*i.* Plan 9 (Plate 6) consisted of the 51.8-m-long (170-ft-long) sheet-pile breakwater of Plan 7; but the existing north breakwater was removed and the depths in the harbor west of the new structure were installed to an el of -1.83 m (-6.0 ft).

*j.* Plan 10 (Plate 6) entailed the elements of Plan 9, but the north structure extension was reduced by 6.1 m (20 ft) in length.

*k.* Plan 11 (Plate 7) included the 51.8-m-long (170-ft-long) breakwater configuration of Plan 9, but the structure was raised from +2.13 m (+7.0 ft) to +6.1 m (+20.0 ft) in height.

*l.* Plan 12 (Plate 8) involved the 51.8-m-long (170-ft-long) breakwater configuration of Plan 9, but a 59.4-m-long (195-ft-long) stone absorber was installed along the west wall of the harbor. The absorber used inside the harbor for this and subsequent plans included 1,815-kg (2-ton) stone installed on a 1V:1.5H slope with an el of +2.13 m (+7.0 ft). The absorber used on the lakeside of the harbor in subsequent plans included 9,070-kg (10-ton) stone installed on the same slopes and el.

*m.* Plan 13 (Plate 8) entailed the 51.8-m-long (170-ft-long) breakwater configuration of Plan 9 with the 59.4-m-long (195-ft-long) stone absorber of Plan 12 and an additional 39-m-long (128-ft-long) stone absorber installed on the lakeward side of the north breakwater.

*n.* Plan 14 (Plate 8) included the 51.8-m-long (170-ft-long) breakwater configuration of Plan 9 with the stone absorbers of Plans 12 and 13 and an additional 42.7-m-long (140-ft-long) stone absorber installed on the harbor side of the north breakwater.

*o.* Plan 15 (Plate 9) consisted of the 51.8-m-long (170-ft-long) breakwater configuration of Plan 9 and the absorbers of Plan 14, but the 59.4-m-long (195-ft-long) absorber along the west wall of the harbor was removed.

*p.* Plan 16 (Plate 10) involved the 51.8-m-long (170-ft-long) breakwater configuration of Plan 9 with a cumulative 137-m (450-ft) length of stone absorber installed along the west wall of the harbor and the harbor sides of the breakwaters.

**Wave-height experiments.** Wave-height experiments were conducted for existing conditions and various improvement plans for representative experimental waves from the various incident directions. Experiments involving some

proposed plans were limited to the most critical direction of wave approach (i.e., 11 deg). Wave-gauge locations are shown in referenced plates.

**Sediment-tracer experiments.** Sediment-tracer experiments were conducted for existing conditions and selected plans of improvement for representative experimental waves from the various incident directions. In most cases, sediment tracer was introduced into the model along the shoreline north of the harbor to define sediment-tracer patterns and subsequent deposition areas.

**Wave-induced current patterns and magnitudes.** Wave-induced current patterns and magnitudes were obtained for existing conditions and selected improvement plans for representative experimental waves from the various incident directions. These experiments were conducted by timing the progress of a dye tracer relative to a known distance on the model surface at selected locations in the model.

**Vessel-wake experiments.** Wave heights were obtained in the harbor as a result of various vessel wakes for existing conditions and selected improvement plans. Experiments were conducted for four vessels entering and leaving the St. Clair River. The maximum wave height in the wave train was measured during these experiments, as opposed to the significant wave height. The vessels were navigated along the channel center line. The types of vessels available and the speeds in which they were navigated are shown below.

| Description of Vessel | Navigation Speed, knots |
|---|---|
| 27-m-long (90-ft-long) Speed boat | 15 |
| 30-m-long (100-ft-long) Cabin cruiser | 12 |
| 183-m-long (600-ft-long) Ore carrier | 7 |
| 210-m-long (690-ft-long) Container vessel | 6 |

## Experimental results

In analyzing results, the relative merits of various improvement plans were based on measured wave heights, wave-induced current patterns and magnitudes, and the movement of sediment-tracer material and deposition areas. Model wave heights were tabulated to show measured values at selected locations. Wave-induced current patterns and magnitudes, and sediment-tracer patterns were superimposed on photographs.

**Existing conditions.** Results of wave-height experiments for existing conditions are presented in Tables 6 (no flow conditions) and 7 (riverflow conditions). For the 11 deg direction, maximum wave heights[1] were 1.8 m (5.9 ft) in the harbor entrance (Gauge 1); 1.43 m (4.7 ft) in the southwest portion of the harbor (Gauge 3); 1.74 m (5.7 ft) in the northwest portion of the harbor (Gauge 4); and

[1] Refers to maximum significant wave heights throughout report.

1.13 m (3.7 ft) along the existing dock (Gauge 5) all for 9.2-sec, 3.02-m (9.9-ft) waves with the +1.07-m (+3.5-ft) swl and no flow conditions. For the 59 deg direction, maximum wave heights were 2.13 m (7.0 ft) in the harbor entrance and 1.25 m (4.1 ft) in the southwest portion of the harbor for no flow conditions; 1.04 m (3.4 ft) in the northwest portion of the harbor for both no flow and riverflow conditions; and 1.8 m (5.9 ft) along the existing dock with riverflow conditions all for 7.0-sec, 2.68-m (8.8-ft) waves with the +1.07-m (+3.5-ft) swl. For 1.22-m (4.0-ft) waves (which occur relatively frequently), wave heights ranged from 0.49 to 0.67 m (1.6 to 2.2 ft) in the harbor entrance; 0.40 to 0.61 m (1.3 to 2.0 ft) in the southwest portion of the harbor; 0.27 to 0.46 m (0.9 to 1.5 ft) in the northwest portion of the harbor; and 0.55 to 0.91 m (1.8 to 3.0 ft) along the existing dock for the 11 deg direction. For the 59 deg direction, 1.22-m (4-ft) incident waves resulted in wave heights ranging from 1.10 to 1.31 m (3.6 to 4.3 ft) in the harbor entrance; 0.98 to 1.19 m (3.2 to 3.9 ft) in the southwest portion of the harbor; 0.49 to 0.64 m (1.6 to 2.1 ft) in the northwest portion of the harbor; and 0.82 to 1.04 m (2.7 to 3.4 ft) along the existing dock.

The general movement of tracer material and subsequent deposits for representative waves from 11 deg are shown in Photos 1-8 for existing conditions. Sediment was introduced along the shoreline north of the harbor. These experiments entailed exposing the tracer material to 6-sec, 1.22-m (4.0-ft) waves for 40 min (model time) and then to 7.9-sec, 2.07-m (6.8-ft) waves for 5 min and were conducted for both swls as well as both riverflow and no flow conditions. In general, tracer material moved southerly along the shoreline and around the north breakwater where it deposited in the entrance channel. Some material then migrated into the harbor. The placement of tracer material prior to experiments from 59 deg is shown in Photo 9, and the general movement of tracer and subsequent deposits for representative waves from 59 deg are shown in Photos 10-17. For these experiments, tracer material was exposed to 5-sec, 1.22-m (4.0-ft) waves for 10 min and then 6-sec, 1.86-m (6.1-ft) waves for 5 min. Experiments were conducted for both riverflow and no flow conditions and for both swls. Tracer material moved southerly around the north breakwater and deposited in the entrance channel where some of it migrated into the harbor.

Current patterns and magnitudes obtained for existing conditions are presented in Photos 18-33 for representative wave conditions for the 11 and 59 deg directions and for no flow and riverflow conditions. For all conditions, currents moved southerly along the shoreline past the harbor and created eddies in the harbor entrance. Maximum velocities were as follows:

| | | | Maximum Velocities, mps (fps) | | |
|---|---|---|---|---|---|
| Wave Direction | swl, m (ft) | Riverflow | North of Harbor | Lakeward of Harbor | South of Harbor |
| 11 deg | +0.52 (+1.7) | No | 0.98 (3.2) | 0.98 (3.2) | 1.01 (3.3) |
| | | Yes | 1.07 (3.5) | 1.28 (4.2) | 1.16 (3.8) |
| | +1.07 (+3.5) | No | 0.76 (2.5) | 0.91 (3.0) | 0.88 (2.9) |
| | | Yes | 1.34 (4.4) | 1.68 (5.5) | 1.22 (4.0) |
| 59 deg | +0.52 (+1.7) | No | 0.88 (2.9) | 1.01 (3.3) | 0.82 (2.7) |
| | | Yes | 0.76 (2.5) | 1.04 (3.4) | 0.98 (3.2) |
| | +1.07 (+3.5) | No | 0.94 (3.1) | 1.10 (3.6) | 1.13 (3.7) |
| | | Yes | 0.73 (2.4) | 1.16 (3.8) | 1.04 (3.4) |

## Table 6
## Wave Heights for Existing Conditions
## (No Flow Conditions)

| Experimental Wave | | | Wave Height, ft, at Indicated Gauge Location | | | | | |
|---|---|---|---|---|---|---|---|---|
| Direction az | Period sec | Height ft | Gauge 1 | Gauge 2 | Gauge 3 | Gauge 4 | Gauge 5 | Gauge 6 |
| swl = +1.7 ft | | | | | | | | |
| 11 | 4.0 | 2.0 | 0.6 | 0.4 | 0.4 | 0.4 | 0.4 | 0.2 |
| | 6.0 | 4.0 | 2.2 | 1.6 | 2.0 | 1.5 | 3.0 | 1.0 |
| | 7.9 | 6.8 | 4.7 | 3.2 | 3.1 | 3.3 | 3.4 | 2.1 |
| | 8.6 | 8.6 | 4.8 | 3.5 | 3.3 | 3.6 | 3.4 | 2.2 |
| | 9.2 | 9.9 | 5.2 | 3.8 | 3.7 | 4.8 | 3.5 | 2.3 |
| 59 | 4.0 | 2.0 | 2.1 | 1.7 | 1.7 | 0.8 | 0.8 | 0.7 |
| | 5.0 | 4.0 | 3.6 | 2.4 | 3.2 | 1.6 | 2.7 | 1.7 |
| | 6.0 | 6.1 | 4.8 | 3.1 | 4.0 | 2.1 | 4.9 | 2.0 |
| | 6.5 | 7.7 | 5.4 | 3.5 | 3.7 | 2.6 | 5.3 | 2.4 |
| | 7.0 | 8.8 | 5.8 | 3.8 | 3.6 | 2.9 | 5.5 | 2.9 |
| swl = +3.5 ft | | | | | | | | |
| 11 | 4.0 | 2.0 | 0.6 | 0.4 | 0.5 | 0.5 | 0.3 | 0.3 |
| | 6.0 | 4.0 | 2.1 | 1.3 | 1.5 | 1.5 | 2.5 | 1.4 |
| | 7.9 | 6.8 | 4.8 | 3.4 | 3.5 | 3.5 | 3.1 | 3.1 |
| | 8.6 | 8.6 | 5.3 | 3.8 | 4.1 | 4.5 | 3.4 | 2.9 |
| | 9.2 | 9.9 | 5.9 | 4.2 | 4.7 | 5.7 | 3.7 | 2.9 |
| 59 | 4.0 | 2.0 | 2.2 | 1.6 | 1.8 | 0.8 | 0.9 | 0.9 |
| | 5.0 | 4.0 | 4.3 | 2.4 | 3.9 | 1.6 | 3.3 | 1.3 |
| | 6.0 | 6.1 | 5.8 | 3.3 | 4.0 | 2.4 | 5.2 | 2.5 |
| | 6.5 | 7.7 | 6.5 | 4.2 | 4.1 | 3.1 | 5.8 | 3.5 |
| | 7.0 | 8.8 | 7.0 | 4.5 | 4.1 | 3.4 | 5.7 | 4.2 |

**Table 7**
**Wave Heights for Existing Conditions**
**(Riverflow Conditions)**

| Experimental Wave | | | Wave Height, ft, at Indicated Gauge Location | | | | | |
|---|---|---|---|---|---|---|---|---|
| Direction az | Period sec | Height ft | Gauge 1 | Gauge 2 | Gauge 3 | Gauge 4 | Gauge 5 | Gauge 6 |
| **swl = +1.7 ft** | | | | | | | | |
| 11 | 4.0 | 2.0 | 1.0 | 0.5 | 0.6 | 0.5 | 0.2 | 0.4 |
| | 6.0 | 4.0 | 1.8 | 1.3 | 1.8 | 0.9 | 2.1 | 0.8 |
| | 7.9 | 6.8 | 3.5 | 2.4 | 2.7 | 2.2 | 2.6 | 1.6 |
| | 8.6 | 8.6 | 4.0 | 2.7 | 2.9 | 2.5 | 2.6 | 1.8 |
| | 9.2 | 9.9 | 4.1 | 2.9 | 3.1 | 2.8 | 2.6 | 1.8 |
| 59 | 4.0 | 2.0 | 2.5 | 2.3 | 1.9 | 1.3 | 1.3 | 1.0 |
| | 5.0 | 4.0 | 4.0 | 2.7 | 3.3 | 2.1 | 3.0 | 2.0 |
| | 6.0 | 6.1 | 5.0 | 3.3 | 3.9 | 2.4 | 5.2 | 2.2 |
| | 6.5 | 7.7 | 5.7 | 3.8 | 3.8 | 3.0 | 5.7 | 2.8 |
| | 7.0 | 8.8 | 6.1 | 4.0 | 3.8 | 3.2 | 5.8 | 3.2 |
| **swl = +3.5 ft** | | | | | | | | |
| 11 | 4.0 | 2.0 | 1.0 | 0.8 | 0.8 | 0.9 | 0.7 | 0.7 |
| | 6.0 | 4.0 | 1.6 | 1.0 | 1.3 | 1.2 | 1.8 | 1.0 |
| | 7.9 | 6.8 | 3.4 | 2.5 | 2.8 | 2.8 | 2.6 | 2.2 |
| | 8.6 | 8.6 | 3.9 | 3.1 | 3.4 | 3.5 | 2.8 | 2.3 |
| | 9.2 | 9.9 | 4.3 | 3.4 | 3.9 | 4.1 | 3.1 | 2.4 |
| 59 | 4.0 | 2.0 | 2.6 | 2.1 | 2.0 | 1.3 | 1.4 | 1.1 |
| | 5.0 | 4.0 | 4.0 | 2.7 | 3.5 | 1.9 | 3.4 | 1.6 |
| | 6.0 | 6.1 | 5.4 | 3.4 | 4.0 | 2.4 | 5.5 | 2.4 |
| | 6.5 | 7.7 | 6.0 | 3.9 | 4.0 | 2.9 | 5.8 | 3.2 |
| | 7.0 | 8.8 | 6.6 | 4.2 | 4.0 | 3.4 | 5.9 | 3.9 |

Typical wave patterns obtained for existing conditions also are shown in Photos 18-33.

Results of vessel-wake experiments with existing conditions installed are presented in Table 8. As noted from these results, the smaller 27-m- (90-ft-) long vessel moving at the greatest speed (15 knots) resulted in the largest waves in the harbor. Maximum waves also occurred as the vessel entered the St. Clair River (as opposed to the vessel leaving the river). Views of the model vessels leaving the St. Clair River and their resulting wakes are shown in Photos 34-37.

**Improvement plans.** The general movement of tracer material and subsequent deposits for Plans 1-8 are shown in Photos 38-60 for representative waves from 11 deg with the +1.07-m (+3.5-ft) swl with riverflow conditions. As for existing conditions, the tracer material was exposed to 6-sec, 1.22-m (4.0-ft) waves for 40 min and then to 7.9-sec, 2.07-m waves for 5 min; however, if shoaling had not occurred in the entrance after this time frame, the plan was exposed to the larger wave for an additional 15 min. Results revealed that minor deposits occurred in the entrance for Plan 1 after the initial 45-min condition (Photo 39). For Plan 2, no shoaling occurred in the entrance after 45 min, but minor tracer deposits were observed after 60 min (Photo 42). Some of the material observed in Photo 42 came over the structure because of overtopping waves. Plans 3 and 4 resulted in essentially no deposits in the entrance after the 60-min condition (Photos 45 and 48). The light traces of sediment material in these photos occurred because of overtopping. Experiments for Plan 5 revealed deposits in the entrance after 60 min (Photo 51); however, Plans 6 and 7 experienced essentially no shoaling for the 60-min condition (Photos 54 and 57). Results of the Plan 8 experiments indicated significant deposits in the entrance for the 60-min condition (Photo 60).

Results of wave height experiments for Plans 1-8 are presented in Table 9 for representative waves from 11 deg for the +1.07-m (+3.5-ft) swl with riverflow conditions. Maximum wave heights obtained were 0.82, 0.88, 0.88, 0.79, 0.67, 0.64, 0.70, and 0.61 m (2.7, 2.9, 2.9, 2.6, 2.2, 2.1, 2.3, and 2.0 ft) in the harbor entrance (Gauge 1); 0.73, 0.73, 0.70, 0.67, 0.61, 0.55, 0.55, and 0.43 m (2.4, 2.4, 2.3, 2.2, 2.0, 1.8, 1.8, and 1.4 ft) in the southwest portion of the harbor (Gauge 3); 0.67, 0.67, 0.67, 0.58, 0.49, 0.49, 0.49, and 0.43 m (2.2, 2.2, 2.2, 1.9, 1.6, 1.6, 1.6, and 1.4 ft) in the northwest portion of the harbor (Gauge 4); and 0.58, 0.64, 0.67, 0.55, 0.46, 0.46, 0.49, and 0.40 m (1.9, 2.1, 2.2, 1.8, 1.5, 1.5, 1.6, and 1.3 ft) along the existing dock (Gauge 5) for Plans 1-8, respectively. For 1.22-m (4.0-ft) incident waves, wave heights were 0.30, 0.27, 0.27, 0.24, 0.24, 0.21, 0.21, and 0.18 m (1.0, 0.9, 0.9, 0.8, 0.8, 0.7, 0.7, and 0.6 ft) in the entrance; 0.21, 0.21, 0.21, 0.21, 0.21, 0.18, 0.18, and 0.12 m (0.7, 0.7, 0.7, 0.7, 0.7, 0.6, 0.6, and 0.4 ft) in the southwest portion of the harbor; 0.18, 0.18, 0.18, 0.15, 0.15, 0.15, 0.15, and 0.12 m (0.6, 0.6, 0.6, 0.5, 0.5, 0.5, 0.5, and 0.4 ft) in the northwest portion of the harbor; and 0.34, 0.34, 0.30, 0.24, 0.27, 0.24, 0.24, and 0.12 m (1.1, 1.1, 1.0, 0.8, 0.9, 0.8, 0.8, and 0.4 ft) along the dock. Typical wave patterns for Plans 1-8 are shown in Photos 61-76 for representative waves with the +1.07-m (+3.5-ft) swl with riverflow conditions.

**Table 8**
**Wave Heights for Existing Conditions for Boat Waves, swl = +3.5 ft (No Flow Conditions)**

| Boat Type<br>Direction | Wave Height, ft, at Indicated Gauge Location | | | | | |
|---|---|---|---|---|---|---|
| | Gauge 1 | Gauge 2 | Gauge 3 | Gauge 4 | Gauge 5 | Gauge 6 |
| 90-ft Speed boat | | | | | | |
| Leaving St. Clair River | 0.7 | 0.2 | 0.4 | 0.2 | 0.4 | 0.4 |
| Entering St. Clair River | 2.6 | 1.5 | 1.8 | 0.5 | 0.7 | 0.6 |
| 100-ft Cabin cruiser | | | | | | |
| Leaving St. Clair River | 0.4 | 0.2 | 0.1 | 0.3 | 0.2 | 0.3 |
| Entering St. Clair River | 0.5 | 0.5 | 0.2 | 0.1 | 0.1 | 0.1 |
| 600-ft Ore carrier | | | | | | |
| Leaving St. Clair River | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Entering St. Clair River | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 |
| 690-ft container vessel | | | | | | |
| Leaving St. Clair River | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Entering St. Clair River | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 |

The general movement of tracer material and subsequent deposits for representative waves from 11 deg are shown in Photos 77-88 for Plan 9. Tracer material was exposed to 6-sec, 1.22-m (4.0-ft) waves for 40 min and then to 7.9-sec, 2.07-m (6.8-ft) waves for 20 min. An intermediate photo was taken after exposure to 6-sec, 1.22-m (4.0-ft) waves for 40 min and 7.9-sec, 2.07-m (6.8-ft) waves after 5 min for a direct comparison of the experiments conducted for existing conditions. In general, tracer material moved southerly along the shoreline and was diverted lakeward around the entrance by the Plan 9 breakwater configuration as it moved downstream. Sediment accumulations were not observed in the entrance for any of the experimental conditions. With no riverflow conditions, it was noted that some material moved over the breakwater because of overtopping and settled in the northeast corner of the harbor. The general movement of tracer material and subsequent deposits for Plan 9 for representative waves from 59 deg are presented in Photos 89-96. Tracer material was exposed to 5-sec, 1.22-m (4.0-ft) waves for 10 min and then 6-sec, 1.86-m (6.1-ft) waves for 5 min. These experiments corresponded to those of existing conditions. Tracer material migrated lakeward with no flow conditions with no material depositing near the harbor entrance. With riverflow conditions, however, material moved southerly around the head of the north breakwater, but did not deposit in the entrance. Only slight deposits occurred in the harbor because of wave overtopping of the structure with riverflow conditions.

Wave-height experiments conducted for Plan 9 are presented in Tables 10 and 11 for no flow and riverflow conditions, respectively. For the 11 deg direction, maximum wave heights were 1.07 m (3.5 ft) in the harbor entrance (Gauge 1); 0.79 m (2.6 ft) in the southwest portion of the harbor (Gauge 3); 0.73 m (2.4 ft) in the northwest portion of the harbor (Gauge 4); and 0.76 m (2.5 ft) along the existing dock (Gauge 5) all for 9.2-sec, 3.02-m (9.9-ft) waves with the +1.07-ft

**Table 9**
**Wave Heights for Plans 1-8 for Waves from 11 Deg, swl = +3.5 ft (Riverflow Conditions)**

| Experimental Wave | | Wave Height, ft, at Indicated Gauge Location | | | | | |
|---|---|---|---|---|---|---|---|
| Period | Height | Gauge 1 | Gauge 2 | Gauge 3 | Gauge 4 | Gauge 5 | Gauge 6 |
| | | | Plan 1 | | | | |
| 4.0 | 2.0 | 0.6 | 0.5 | 0.5 | 0.5 | 0.4 | 0.4 |
| 6.0 | 4.0 | 1.0 | 0.7 | 0.7 | 0.6 | 1.1 | 0.9 |
| 7.9 | 6.8 | 2.0 | 1.4 | 1.6 | 1.3 | 1.4 | 1.6 |
| 8.6 | 8.6 | 2.4 | 1.7 | 1.9 | 1.7 | 1.6 | 1.6 |
| 9.2 | 9.9 | 2.7 | 2.0 | 2.4 | 2.2 | 1.9 | 1.7 |
| | | | Plan 2 | | | | |
| 4.0 | 2.0 | 0.7 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 |
| 6.0 | 4.0 | 0.9 | 0.7 | 0.7 | 0.6 | 1.1 | 0.8 |
| 7.9 | 6.8 | 2.1 | 1.4 | 1.5 | 1.4 | 1.5 | 1.8 |
| 8.6 | 8.6 | 2.3 | 1.7 | 1.7 | 1.7 | 1.7 | 1.8 |
| 9.2 | 9.9 | 2.9 | 1.9 | 2.4 | 2.2 | 2.1 | 1.8 |
| | | | Plan 3 | | | | |
| 4.0 | 2.0 | 0.6 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| 6.0 | 4.0 | 0.9 | 0.6 | 0.7 | 0.6 | 1.0 | 0.8 |
| 7.9 | 6.8 | 2.1 | 1.4 | 1.5 | 1.4 | 1.4 | 1.8 |
| 8.6 | 8.6 | 2.3 | 1.6 | 1.6 | 1.8 | 1.7 | 1.8 |
| 9.2 | 9.9 | 2.9 | 1.9 | 2.3 | 2.2 | 2.2 | 1.8 |
| | | | Plan 4 | | | | |
| 4.0 | 2.0 | 0.4 | 0.3 | 0.3 | 0.4 | 0.2 | 0.3 |
| 6.0 | 4.0 | 0.8 | 0.5 | 0.7 | 0.5 | 0.8 | 0.7 |
| 7.9 | 6.8 | 1.9 | 1.3 | 1.5 | 1.3 | 1.3 | 1.6 |
| 8.6 | 8.6 | 2.2 | 1.5 | 1.7 | 1.6 | 1.5 | 1.7 |
| 9.2 | 9.9 | 2.6 | 1.8 | 2.2 | 1.9 | 1.8 | 1.6 |
| | | | Plan 5 | | | | |
| 4.0 | 2.0 | 0.6 | 0.5 | 0.5 | 0.4 | 0.4 | 0.3 |
| 6.0 | 4.0 | 0.8 | 0.6 | 0.7 | 0.5 | 0.9 | 0.6 |
| 7.9 | 6.8 | 1.7 | 1.2 | 1.4 | 1.2 | 1.2 | 1.4 |
| 8.6 | 8.6 | 2.0 | 1.5 | 1.6 | 1.4 | 1.3 | 1.4 |
| 9.2 | 9.9 | 2.2 | 1.7 | 2.0 | 1.6 | 1.5 | 1.4 |

*(Continued)*

**Table 9 (Concluded)**

| Experimental Wave | | Wave Height, ft, at Indicated Gauge Location | | | | | |
|---|---|---|---|---|---|---|---|
| Period | Height | Gauge 1 | Gauge 2 | Gauge 3 | Gauge 4 | Gauge 5 | Gauge 6 |
| **Plan 6** | | | | | | | |
| 4.0 | 2.0 | 0.6 | 0.4 | 0.4 | 0.4 | 0.3 | 0.3 |
| 6.0 | 4.0 | 0.7 | 0.5 | 0.6 | 0.5 | 0.8 | 0.6 |
| 7.9 | 6.8 | 1.6 | 1.1 | 1.2 | 1.1 | 1.1 | 1.4 |
| 8.6 | 8.6 | 1.8 | 1.4 | 1.4 | 1.3 | 1.3 | 1.4 |
| 9.2 | 9.9 | 2.1 | 1.6 | 1.8 | 1.6 | 1.5 | 1.4 |
| **Plan 7** | | | | | | | |
| 4.0 | 2.0 | 0.5 | 0.4 | 0.4 | 0.3 | 0.3 | 0.3 |
| 6.0 | 4.0 | 0.7 | 0.5 | 0.6 | 0.5 | 0.8 | 0.6 |
| 7.9 | 6.8 | 1.5 | 1.1 | 1.2 | 1.1 | 1.2 | 1.4 |
| 8.6 | 8.6 | 1.8 | 1.4 | 1.3 | 1.4 | 1.4 | 1.4 |
| 9.2 | 9.9 | 2.3 | 1.6 | 1.8 | 1.6 | 1.6 | 1.4 |
| **Plan 8** | | | | | | | |
| 4.0 | 2.0 | 0.4 | 0.1 | 0.4 | 0.3 | 0.7 | 0.3 |
| 6.0 | 4.0 | 0.6 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 |
| 7.9 | 6.8 | 1.4 | 0.8 | 0.8 | 0.8 | 0.7 | 0.9 |
| 8.6 | 8.6 | 1.8 | 1.1 | 1.1 | 1.2 | 1.0 | 1.1 |
| 9.2 | 9.9 | 2.0 | 1.3 | 1.4 | 1.4 | 1.3 | 1.1 |

(+3.5-ft) swl and no flow conditions. For the 59 deg direction, maximum wave heights were 1.01 m (3.3 ft) in the entrance; 0.88 m (2.9 ft) in the southwest portion of the harbor; 0.85 m (2.8 ft) in the northwest portion of the harbor; and 1.04 m (3.4 ft) along the existing dock all for 7.0-sec, 2.68-m (8.8-ft) waves with the +1.07-m (+3.5-ft) swl with riverflow conditions. For 1.22-m (4.0-ft) waves, wave heights ranged from 0.18 to 0.24 m (0.6 to 0.8 ft) in the entrance; 0.18 to 0.24 m (0.6 to 0.8 ft) in the southwest portion of the harbor; 0.09 to 0.15 m (0.3 to 0.5 ft) in the northwest portion of the harbor; and 0.21 to 0.30 m (0.7 to 1.0 ft) along the dock for the 11 deg direction. For the 59 deg direction, 1.22-m (4.0-ft) incident waves resulted in heights ranging from 0.37 to 0.55 m (1.2 to 1.8 ft) in the entrance; 0.34 to 0.55 m (1.1 to 1.8 ft) in the southwest portion of the harbor; 0.18 to 0.34 m (0.6 to 1.1 ft) in the northwest portion of the harbor; and 0.37 to 0.64 m (1.2 to 2.1 ft) along the existing dock.

**Table 10**
**Wave Heights for Plan 9**
**(No Flow Conditions)**

| Experimental Wave | | | Wave Height, ft, at Indicated Gauge Location | | | | | |
|---|---|---|---|---|---|---|---|---|
| Direction az | Period sec | Height ft | Gauge 1 | Gauge 2 | Gauge 3 | Gauge 4 | Gauge 5 | Gauge 6 |
| swl = +1.7 ft | | | | | | | | |
| 11 | 4.0 | 2.0 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 | 0.1 |
| | 6.0 | 4.0 | 0.8 | 0.4 | 0.8 | 0.3 | 1.0 | 0.5 |
| | 7.9 | 6.8 | 2.4 | 1.5 | 1.4 | 1.3 | 1.4 | 1.4 |
| | 8.6 | 8.6 | 2.9 | 2.1 | 2.0 | 1.7 | 1.9 | 1.8 |
| | 9.2 | 9.9 | 3.0 | 2.3 | 2.1 | 1.9 | 2.0 | 2.0 |
| 59 | 4.0 | 2.0 | 0.6 | 0.4 | 0.5 | 0.3 | 0.3 | 0.4 |
| | 5.0 | 4.0 | 1.2 | 0.8 | 1.1 | 0.7 | 1.2 | 1.0 |
| | 6.0 | 6.1 | 2.0 | 1.5 | 1.9 | 1.2 | 2.2 | 1.5 |
| | 6.5 | 7.7 | 2.3 | 1.6 | 1.8 | 1.4 | 2.2 | 1.7 |
| | 7.0 | 8.8 | 2.5 | 1.8 | 1.8 | 1.6 | 2.3 | 1.8 |
| swl = +3.5 ft | | | | | | | | |
| 11 | 4.0 | 2.0 | 0.1 | 0.1 | 0.2 | 0.2 | 0.1 | 0.2 |
| | 6.0 | 4.0 | 0.8 | 0.4 | 0.6 | 0.5 | 0.8 | 0.7 |
| | 7.9 | 6.8 | 2.5 | 2.0 | 1.7 | 1.6 | 1.7 | 2.0 |
| | 8.6 | 8.6 | 3.2 | 3.1 | 2.4 | 2.2 | 2.2 | 2.4 |
| | 9.2 | 9.9 | 3.5 | 2.9 | 2.6 | 2.4 | 2.5 | 2.2 |
| 59 | 4.0 | 2.0 | 0.7 | 0.4 | 0.7 | 0.3 | 0.3 | 0.5 |
| | 5.0 | 4.0 | 1.2 | 0.7 | 1.1 | 0.6 | 1.4 | 0.8 |
| | 6.0 | 6.1 | 1.9 | 1.5 | 1.7 | 1.2 | 2.0 | 1.7 |
| | 6.5 | 7.7 | 2.5 | 2.1 | 2.1 | 1.9 | 2.5 | 2.2 |
| | 7.0 | 8.8 | 2.9 | 2.5 | 2.4 | 2.2 | 2.7 | 2.6 |

## Table 11
## Wave Heights for Plan 9
## (Riverflow Conditions)

| Experimental Wave | | | Wave Height, ft, at Indicated Gauge Location | | | | | |
|---|---|---|---|---|---|---|---|---|
| Direction az | Period sec | Height ft | Gauge 1 | Gauge 2 | Gauge 3 | Gauge 4 | Gauge 5 | Gauge 6 |
| swl = +1.7 ft | | | | | | | | |
| 11 | 4.0 | 2.0 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 |
| | 6.0 | 4.0 | 0.6 | 0.3 | 0.8 | 0.3 | 0.8 | 0.5 |
| | 7.9 | 6.8 | 1.8 | 1.3 | 1.3 | 1.1 | 1.3 | 1.2 |
| | 8.6 | 8.6 | 2.3 | 1.7 | 1.7 | 1.4 | 1.6 | 1.4 |
| | 9.2 | 9.9 | 2.3 | 1.8 | 1.9 | 1.6 | 1.7 | 1.6 |
| 59 | 4.0 | 2.0 | 1.3 | 0.9 | 0.7 | 0.7 | 0.6 | 0.7 |
| | 5.0 | 4.0 | 1.5 | 1.0 | 1.3 | 1.0 | 1.3 | 1.2 |
| | 6.0 | 6.1 | 2.3 | 1.6 | 2.1 | 1.4 | 2.5 | 1.8 |
| | 6.5 | 7.7 | 2.7 | 1.9 | 2.2 | 1.7 | 2.5 | 2.2 |
| | 7.0 | 8.8 | 2.9 | 2.1 | 2.1 | 2.0 | 2.8 | 2.4 |
| swl = +3.5 ft | | | | | | | | |
| 11 | 4.0 | 2.0 | 0.5 | 0.2 | 0.3 | 0.3 | 0.2 | 0.3 |
| | 6.0 | 4.0 | 0.6 | 0.3 | 0.6 | 0.4 | 0.7 | 0.6 |
| | 7.9 | 6.8 | 1.6 | 1.2 | 1.3 | 1.0 | 1.2 | 1.5 |
| | 8.6 | 8.6 | 2.0 | 1.7 | 1.6 | 1.4 | 1.6 | 1.7 |
| | 9.2 | 9.9 | 2.4 | 1.8 | 1.9 | 1.8 | 1.9 | 1.7 |
| 59 | 4.0 | 2.0 | 1.1 | 0.9 | 0.9 | 0.6 | 0.7 | 0.8 |
| | 5.0 | 4.0 | 1.8 | 1.3 | 1.8 | 1.1 | 2.1 | 1.3 |
| | 6.0 | 6.1 | 2.3 | 1.8 | 2.1 | 1.5 | 2.5 | 1.9 |
| | 6.5 | 7.7 | 2.9 | 2.4 | 2.4 | 2.2 | 2.8 | 2.5 |
| | 7.0 | 8.8 | 3.3 | 3.1 | 2.9 | 2.8 | 3.4 | 3.2 |

Current patterns and magnitudes obtained for Plan 9 are presented in Photos 97-112 for various wave conditions for the 11 and 59 deg directions and for both no flow and riverflow conditions. For all conditions, currents moved southerly along the shoreline past the harbor and created weak eddies inside the harbor entrance. Maximum velocities were as follows:

| Wave Direction | swl, m (ft) | Riverflow | Maximum Velocities, mps (fps) | | |
|---|---|---|---|---|---|
| | | | North of Harbor | Lakeward of Harbor | South of Harbor |
| 11 deg | +0.52 (+1.7) | No | 0.55 (1.8) | 0.34 (1.1) | 0.70 (2.3) |
| | | Yes | 1.10 (3.6) | 1.37 (4.5) | 0.76 (2.5) |
| | +1.07 (+3.5) | No | 0.79 (2.6) | 0.82 (2.7) | 0.18 (0.6) |
| | | Yes | 0.79 (2.6) | 1.04 (3.4) | 0.88 (2.9) |
| 59 deg | +0.52 (+1.7) | No | 0.58 (1.9) | 0.91 (3.0) | 0.55 (1.8) |
| | | Yes | 0.88 (2.9) | 1.04 (3.4) | 0.88 (2.9) |
| | +1.07 (+3.5) | No | 0.55 (1.8) | 0.64 (2.1) | 0.49 (1.6) |
| | | Yes | 0.98 (3.2) | 1.46 (4.8) | 1.25 (4.1) |

Typical wave patterns obtained for Plan 9 also are shown in Photos 97-112.

Results of vessel-wake experiments for Plan 9 are presented in Table 12. Similar to existing conditions, the smaller 27-m (90-ft) vessel moving at the greatest speed (15 knots) produced the largest waves in the harbor. However, in converse to existing conditions, maximum waves occurred as the vessel was leaving the St. Clair River (as opposed to the vessel entering the river). Views of the model vessels leaving the St. Clair River and their resulting wakes for Plan 9 are shown in Photos 113-116.

The general movement of tracer material and subsequent deposits for Plan 10 are shown in Photos 117-128 for representative waves from 11 deg. Similar to Plan 9, tracer material was exposed to 6-sec, 1.22-m (4.0-ft) waves for 40 min and then to 7.9-sec, 2.07-m (6.8-ft) waves for 20 min. In addition, an intermediate photo was obtained after exposure to 6-sec, 1.22-m (4.0-ft) waves for 40 min and 7.9-sec, 2.07-m (6.8-ft) waves for 5 min for direct comparisons with existing conditions. In general, tracer material moved southerly along the shoreline and was diverted lakeward around the entrance by the Plan 10 breakwater configuration. Sediment accumulations were not observed in the entrance for any of the experimental conditions. Some material was carried over the breakwater by wave overtopping and settled in the western portion of the harbor, particularly for no riverflow conditions. The general movement of tracer material and subsequent deposits for representative waves from 59 deg are presented in Photos 129-136 for Plan 10. Tracer material was exposed to 5-sec, 1.22-m (4.0-ft) waves for 10 min and 6-sec, 1.86-m (6.1-ft) waves for 5 min. These conditions corresponded to those of existing conditions and Plan 9. Tracer material migrated lakeward with no flow conditions with no material depositing near the harbor entrance. With riverflow conditions, however, material moved southerly around the head of the north breakwater and resulted in slight deposits in the harbor entrance. Slight deposits also occurred in the western portion of the harbor as a result of being carried over the structure because of wave overtopping for some conditions.

Results of wave-height experiments for Plan 10 are presented in Tables 13 and 14, respectively, for no flow and riverflow conditions. For the 11 deg direction, maximum wave heights were 1.01 m (3.3 ft) in the harbor entrance (Gauge 1); 0.85 m (2.8 ft) in the southwest portion of the harbor (Gauge 3); 0.73 m (2.4 ft) in the northwest portion of the harbor (Gauge 4); and 0.73 m (2.4 ft) along the existing dock (Gauge 5) all for 9.2-sec, 3.02-m (9.9-ft) waves

**Table 12**
**Wave Heights for Plan 9 for Boat Waves, swl = +3.5 ft (No Flow Conditions)**

| Boat Type Direction | Wave Height, ft, at Indicated Gauge Location | | | | | |
|---|---|---|---|---|---|---|
| | Gauge 1 | Gauge 2 | Gauge 3 | Gauge 4 | Gauge 5 | Gauge 6 |
| 90-ft Speed boat | | | | | | |
| Leaving St. Clair River | 1.0 | 0.4 | 0.4 | 0.4 | 0.7 | 0.5 |
| Entering St. Clair River | 0.4 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| 100-ft Cabin cruiser | | | | | | |
| Leaving St. Clair River | 0.8 | 0.2 | 0.1 | 0.4 | 0.3 | 0.3 |
| Entering St. Clair River | 0.6 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 |
| 600-ft Ore carrier | | | | | | |
| Leaving St. Clair River | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Entering St. Clair River | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 |
| 690-ft Container vessel | | | | | | |
| Leaving St. Clair River | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Entering St. Clair River | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |

with the +1.07-m (+3.5-ft) swl and no flow conditions. For the 59 deg direction, maximum wave heights were 1.10 m (3.6 ft) in the harbor entrance; 0.82 m (2.7 ft) in the southwest portion of the harbor; 0.73 m (2.4 ft) in the northwest portion of the harbor; and 0.98 m (3.2 ft) along the existing dock all for 7.0-sec, 2.68-m (8.8-ft) waves with the +1.07-m (+3.5-ft) swl with river flow conditions. For 1.22-m (4.0-ft) waves, heights ranged from 0.21 to 0.27 m (0.7 to 0.9 ft) in the entrance; 0.18 to 0.27 m (0.6 to 0.9 ft) in the southwest portion of the harbor; 0.9 to 0.15 m (0.3 to 0.5 ft) in the northwest portion of the harbor; and 0.21 to 0.37 m (0.7 to 1.2 ft) along the dock for the 11 deg direction. For the 59 deg direction, 1.22-m (4.0-ft) incident waves resulted in heights ranging from 0.37 to 0.58 m (1.2 to 1.9 ft) in the entrance; 0.34 to 0.55 m (1.1 to 1.8 ft) in the southwest portion of the harbor; 0.21 to 0.34 m (0.7 to 1.1 ft) in the northwest portion of the harbor; and 0.34 to 0.70 m (1.1 to 2.3 ft) along the existing dock.

Current patterns and magnitudes obtained for Plan 10 are presented in Photos 137-152 for various wave conditions for the 11 and 59 deg directions for both no flow and riverflow conditions. For all conditions, currents moved southerly along the shoreline past the harbor and created weak eddies inside the harbor entrance. Maximum velocities were as follows:

| Wave Direction | swl, m (ft) | Riverflow | Maximum Velocities, mps (fps) | | |
|---|---|---|---|---|---|
| | | | North of Harbor | Lakeward of Harbor | South of Harbor |
| 11 deg | +0.52 (+1.7) | No | 1.07 (3.5) | 0.40 (1.3) | 0.40 (1.3) |
| | | Yes | 0.70 (2.3) | 0.94 (3.1) | 0.98 (3.2) |
| | +1.07 (+3.5) | No | 0.70 (2.3) | 0.98 (3.2) | 0.18 (0.6) |
| | | Yes | 0.58 (1.9) | 0.98 (3.2) | 0.30 (1.0) |
| 59 deg | +0.52 (+1.7) | No | 0.70 (2.3) | 0.98 (3.2) | 0.70 (2.3) |
| | | Yes | 0.73 (2.4) | 1.05 (3.4) | 0.73 (2.4) |
| | +1.07 (+3.5) | No | 0.64 (2.1) | 0.82 (2.7) | 0.55 (1.8) |
| | | Yes | 0.98 (3.2) | 0.85 (2.8) | 0.70 (2.3) |

**Table 13**
**Wave Heights for Plan 10**
**(No Flow Conditions)**

| Experimental Wave | | | Wave Height, ft, at Indicated Gauge Location | | | | | |
|---|---|---|---|---|---|---|---|---|
| Direction az | Period sec | Height ft | Gauge 1 | Gauge 2 | Gauge 3 | Gauge 4 | Gauge 5 | Gauge 6 |
| swl = +1.7 ft | | | | | | | | |
| 11 | 4.0 | 2.0 | 0.2 | 0.1 | 0.2 | 0.1 | 0.1 | 0.2 |
| | 6.0 | 4.0 | 0.9 | 0.5 | 0.9 | 0.4 | 1.2 | 0.7 |
| | 7.9 | 6.8 | 2.2 | 1.3 | 1.4 | 1.1 | 1.4 | 1.4 |
| | 8.6 | 8.6 | 2.7 | 1.8 | 1.8 | 1.5 | 1.7 | 1.7 |
| | 9.2 | 9.9 | 2.9 | 2.1 | 2.1 | 1.7 | 1.8 | 1.9 |
| 59 | 4.0 | 2.0 | 0.7 | 0.6 | 0.6 | 0.4 | 0.2 | 0.4 |
| | 5.0 | 4.0 | 1.2 | 0.8 | 1.1 | 0.7 | 1.1 | 1.0 |
| | 6.0 | 6.1 | 2.1 | 1.5 | 1.9 | 1.2 | 2.2 | 1.4 |
| | 6.5 | 7.7 | 2.6 | 1.7 | 2.0 | 1.4 | 2.3 | 1.6 |
| | 7.0 | 8.8 | 2.8 | 1.9 | 1.8 | 1.5 | 2.3 | 1.7 |
| swl = +3.5 ft | | | | | | | | |
| 11 | 4.0 | 2.0 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| | 6.0 | 4.0 | 0.9 | 0.5 | 0.7 | 0.5 | 0.9 | 0.7 |
| | 7.9 | 6.8 | 2.2 | 1.6 | 1.6 | 1.3 | 1.4 | 1.9 |
| | 8.6 | 8.6 | 2.9 | 2.6 | 2.5 | 2.2 | 2.1 | 2.6 |
| | 9.2 | 9.9 | 3.3 | 2.8 | 2.8 | 2.4 | 2.4 | 2.6 |
| 59 | 4.0 | 2.0 | 0.7 | 0.5 | 0.6 | 0.3 | 0.2 | 0.5 |
| | 5.0 | 4.0 | 1.4 | 1.1 | 1.3 | 0.8 | 1.7 | 0.9 |
| | 6.0 | 6.1 | 2.4 | 1.7 | 2.0 | 1.4 | 2.2 | 1.8 |
| | 6.5 | 7.7 | 3.0 | 2.3 | 2.3 | 1.8 | 2.7 | 2.3 |
| | 7.0 | 8.8 | 3.1 | 2.4 | 2.2 | 1.9 | 2.5 | 2.4 |

## Table 14
## Wave Heights for Plan 10
## (Riverflow Conditions)

| Experimental Wave | | | Wave Height, ft, at Indicated Gauge Location | | | | | |
|---|---|---|---|---|---|---|---|---|
| Direction az | Period sec | Height ft | Gauge 1 | Gauge 2 | Gauge 3 | Gauge 4 | Gauge 5 | Gauge 6 |
| swl = +1.7 ft | | | | | | | | |
| 11 | 4.0 | 2.0 | 0.4 | 0.1 | 0.3 | 0.1 | 0.1 | 0.2 |
| | 6.0 | 4.0 | 0.7 | 0.3 | 0.7 | 0.3 | 0.7 | 0.6 |
| | 7.9 | 6.8 | 1.8 | 1.2 | 1.2 | 1.0 | 1.3 | 1.1 |
| | 8.6 | 8.6 | 2.5 | 1.8 | 1.6 | 1.2 | 1.6 | 1.3 |
| | 9.2 | 9.9 | 2.6 | 1.9 | 1.9 | 1.5 | 1.8 | 1.5 |
| 59 | 4.0 | 2.0 | 1.4 | 1.0 | 1.1 | 0.8 | 0.7 | 0.9 |
| | 5.0 | 4.0 | 1.8 | 1.3 | 1.5 | 1.1 | 1.8 | 1.5 |
| | 6.0 | 6.1 | 2.6 | 2.0 | 2.5 | 1.7 | 3.0 | 2.1 |
| | 6.5 | 7.7 | 3.1 | 2.3 | 2.4 | 1.9 | 3.0 | 2.5 |
| | 7.0 | 8.8 | 3.5 | 2.6 | 2.3 | 2.2 | 3.1 | 2.9 |
| swl = +3.5 ft | | | | | | | | |
| 11 | 4.0 | 2.0 | 0.6 | 0.4 | 0.4 | 0.3 | 0.2 | 0.4 |
| | 6.0 | 4.0 | 0.7 | 0.4 | 0.6 | 0.4 | 0.7 | 0.6 |
| | 7.9 | 6.8 | 1.6 | 1.1 | 1.2 | 0.9 | 1.0 | 1.8 |
| | 8.6 | 8.6 | 2.0 | 1.6 | 1.7 | 1.4 | 1.4 | 1.8 |
| | 9.2 | 9.9 | 2.2 | 1.8 | 2.0 | 1.7 | 1.7 | 2.0 |
| 59 | 4.0 | 2.0 | 1.3 | 1.0 | 1.2 | 0.7 | 0.7 | 0.9 |
| | 5.0 | 4.0 | 1.9 | 1.4 | 1.8 | 1.1 | 2.3 | 1.3 |
| | 6.0 | 6.1 | 2.7 | 2.1 | 2.3 | 1.6 | 3.0 | 1.9 |
| | 6.5 | 7.7 | 3.2 | 2.6 | 2.5 | 2.0 | 3.1 | 2.5 |
| | 7.0 | 8.8 | 3.6 | 3.1 | 2.7 | 2.4 | 3.2 | 3.1 |

Typical wave patterns obtained for Plan 10 also are shown in Photos 137-152.

Results of vessel-wake experiments for Plan 10 are presented in Table 15. Similar to existing conditions and Plan 9, the smaller 27-m (90-ft) vessel moving at the greatest speed (15 knots) produced the largest waves in the harbor. However, in converse to existing conditions and similar to Plan 9, maximum waves occurred as the vessel was leaving the St. Clair River (as opposed to the vessel entering the river). Views of the model vessels leaving the St. Clair River and their resulting wakes are shown in Photos 153-156.

Results of wave-height experiments for Plans 11-16 are presented in Table 16 for representative waves from 11 deg with the +1.07-m (+3.5-ft) swl and no flow conditions. Maximum wave heights obtained for 7.9-sec, 2.07-m (6.8-ft) waves were 0.67, 0.73, 0.61, 0.52, 0.55, and 0.67 m (2.2, 2.4, 2.0, 1.7, 1.8, and 2.2 ft) in the harbor entrance (Gauge 1); 0.49, 0.40, 0.34, 0.30, 0.30, and 0.34 m (1.6, 1.3, 1.1, 1.0, 1.0, and 1.1 ft) in the southwest portion of the harbor (Gauge 3); 0.37, 0.37, 0.30, 0.37, 0.30, and 0.37 m (1.2, 1.2, 1.0, 1.2, 1.0, and 1.2 ft) in the northwest portion of the harbor (Gauge 4); and 0.43, 0.37, 0.34, 0.37, 0.34, and 0.37 m (1.4, 1.2, 1.1, 1.2, 1.1, and 1.2 ft) along the existing dock (Gauge 5) for Plans 11-16, respectively. For 6-sec, 1.22-m (4.0-ft) waves, maximum wave heights were 0.21, 0.24, 0.24, 0.21, 0.24, and 0.21 m (0.7, 0.8, 0.8, 0.7, 0.8, and 0.7 ft) in the harbor entrance; 0.18, 0.12, 0.12, 0.12, 0.12, and 0.12 m (0.6, 0.4, 0.4, 0.4, 0.4, and 0.4 ft) in the southwest portion of the harbor; 0.15, 0.18, 0.15, 0.15, 0.15, and 0.18 m (0.5, 0.6, 0.5, 0.5, 0.5, and 0.6 ft) in the northwest portion of the harbor; and 0.27, 0.21, 0.21, 0.18, 0.27, and 0.18 m (0.9, 0.7, 0.7, 0.6, 0.9, and 0.6 ft) along the existing dock.

**Discussion of experimental results.** Results of wave-height experiments for existing conditions revealed rough and turbulent waves in the existing harbor. Very confused wave patterns were observed because of reflected wave energy off the vertical walls in the harbor. Wave heights in the harbor were 1.19 m (3.9 ft) for typical storm-wave conditions (1.22-m (4.0-ft) incident waves) and 1.8 m (5.9 ft) for extreme storm-wave conditions (2.68-m (8.8-ft) incident waves). Maximum wave heights in the harbor generally occurred for waves from 59 deg with the higher +1.07-m (+3.5-ft) swl and riverflow conditions. It was noted, however, that waves from 11 deg were larger in the harbor for no flow conditions.

The 11 deg direction is predominant since about 91 percent of wave occurrences are from this direction.

Sediment-tracer results for existing conditions indicated that wave action will move sediment southerly around the north breakwater and into the harbor entrance with some migrating into the harbor. These patterns and subsequent deposits occurred for every experimental wave series for both the 11 and 59 deg directions, both the +0.52-m (+1.7-ft) and +1.07-m (+3.5-ft) swls, and both riverflow and no flow conditions.

**Table 15**
**Wave Heights for Plan 10 for Boat Waves, swl = +3.5 ft (No Flow Conditions)**

| Boat Type Direction | Wave Height, ft, at Indicated Gauge Location | | | | | |
|---|---|---|---|---|---|---|
| | Gauge 1 | Gauge 2 | Gauge 3 | Gauge 4 | Gauge 5 | Gauge 6 |
| 90-ft Speed boat | | | | | | |
| Leaving St. Clair River | 1.2 | 0.7 | 0.5 | 0.5 | 0.8 | 0.6 |
| Entering St. Clair River | 0.7 | 0.4 | 0.4 | 0.3 | 0.4 | 0.3 |
| 100-ft Cabin cruiser | | | | | | |
| Leaving St. Clair River | 1.3 | 0.5 | 0.3 | 0.6 | 0.4 | 0.4 |
| Entering St. Clair River | 0.7 | 0.4 | 0.4 | 0.2 | 0.3 | 0.3 |
| 600-ft Ore carrier | | | | | | |
| Leaving St. Clair River | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Entering St. Clair River | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| 690-ft Container vessel | | | | | | |
| Leaving St. Clair River | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Entering St. Clair River | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 |

**Table 16**
**Wave Heights for Plans 11-16 for Waves from 11 deg, swl = +3.5 ft (No Flow Conditions)**

| Experimental Wave | | | Wave Height, ft, at Indicated Gauge Location | | | | | |
|---|---|---|---|---|---|---|---|---|
| Plan No. | Period sec | Height ft | Gauge 1 | Gauge 2 | Gauge 3 | Gauge 4 | Gauge 5 | Gauge 6 |
| 11 | 6.0 | 4.0 | 0.7 | 0.5 | 0.6 | 0.5 | 0.9 | 0.7 |
| | 7.9 | 6.8 | 2.2 | 1.5 | 1.6 | 1.2 | 1.4 | 1.9 |
| 12 | 6.0 | 4.0 | 0.8 | 0.5 | 0.4 | 0.6 | 0.7 | 0.8 |
| | 7.9 | 6.8 | 2.4 | 1.8 | 1.3 | 1.2 | 1.2 | 1.9 |
| 13 | 6.0 | 4.0 | 0.8 | 0.5 | 0.4 | 0.5 | 0.7 | 0.8 |
| | 7.9 | 6.8 | 2.0 | 1.3 | 1.1 | 1.0 | 1.1 | 1.9 |
| 14 | 6.0 | 4.0 | 0.7 | 0.4 | 0.4 | 0.5 | 0.6 | 0.8 |
| | 7.9 | 6.8 | 1.7 | 1.2 | 1.0 | 1.2 | 1.2 | 1.7 |
| 15 | 6.0 | 4.0 | 0.8 | 0.5 | 0.4 | 0.5 | 0.9 | 0.7 |
| | 7.9 | 6.8 | 1.8 | 1.4 | 1.0 | 1.0 | 1.1 | 1.7 |
| 16 | 6.0 | 4.0 | 0.7 | 0.5 | 0.4 | 0.6 | 0.6 | 0.7 |
| | 7.9 | 6.8 | 2.2 | 1.5 | 1.1 | 1.2 | 1.2 | 1.5 |

Wave-height experiments for the initial improvement plans (Plans 1-8) indiated that Plan 8 provided slightly better wave protection to the harbor than the other plans. For typical storm-wave conditions, wave heights in the harbor for Plan 8 were 0.03 to 0.21 m (0.1 to 0.7 ft) less than the other improvement plans; and for extreme storm-wave conditions, from 0.06 to 0.30 m (0.2 to 1.0 ft) less than the other plans. An evaluation of the sediment-tracer experiments, however, revealed that Plan 8 resulted in significantly more shoaling in the harbor entrance relative to the other plans. The breakwater configurations of Plans 3, 4, 6, and 7 experienced essentially no shoaling of the harbor entrance. An evaluation of wave conditions in the harbor for these plans indicated that Plans 6 and 7 provided greater wave protection than Plans 3 and 4. Therefore, the breakwater configurations of Plans 6 and 7 were considered optimum at this point with respect to wave conditions in the harbor and the prevention of shoaling in the entrance channel. Based on model results, these breakwater layouts were used as a basis for subsequent experiments.

The breakwater layouts of Plans 9 and 10 were similar to those of Plans 7 and 6, respectively; but a portion of the existing north breakwater was removed, and the depths were reduced on the harbor side of the new structure. A comparison of wave heights obtained for Plans 9 and 10 revealed that the results were similar. In some instances, the Plan 9 breakwater configuration resulted in slightly larger wave heights at a particular location in the harbor; and in some cases, the Plan 10 layout resulted in slightly larger values. A comparison of wave heights obtained for Plans 9 and 10 with those of existing conditions indicated, however, that both plans significantly reduced wave heights in the harbor. The Plan 9 breakwater configuraion resulted in wave-height reductions ranging from 31 to 71 percent in the harbor considering all hydrodynamic conditions; and the Plan 10 breakwater resulted in reductions ranging from 34 to 67 percent.

Sediment-tracer experiments for Plans 9 and 10 revealed similar patterns and subsequent deposits for waves from 11 deg with both no flow and riverflow conditions. Waves from 59 deg revealed similar patterns and deposits for no flow conditions; however, with riverflow conditions, slight deposits occurred in the harbor entrance for Plan 10. These results indicate that the Plan 9 breakwater configuration will provide slightly more shoaling protection of the harbor entrance than that of Plan 10. Both plans, however, are a significant improvement over existing conditions, which shoal for every experimental series.

Wave-induced current patterns and magnitudes for Plans 9 and 10 revealed similar results, with currents moving southerly along the shoreline and past the harbor. Weak eddies also formed at the harbor entrance. The breakwaters of Plans 9 and 10 deflected currents slightly lakeward as they passed the harbor versus those of existing conditions. Once past the harbor, currents moved southerly along the shoreline for all situations.

A comparison of wave heights in the harbor as a result of boat wakes indicated that Plan 9 would result in slightly smaller values than Plan 10 for the 27- and 30-m-long (90- and 100-ft-long) vessels. For the 183- and 210-m-long (600- and 630-ft-long) vessels, wave heights in the harbor were similar. A comparison of boat wakes for the Plans 9 and 10 layouts with existing conditions

indicated a significant reduction in wave heights for the improvement plans versus existing conditions for the 27-m-long (90-ft-long) vessel. Plan 9 resulted in similar wave heights as existing conditions for the 30-, 183-, and 210-m-long (100-, 600-, and 630-ft-long) vessels, and Plan 10 revealed similar conditions for the 183- and 210-m-long (600- and 630-ft-long) vessels as existing conditions. For the 30-m-long (100-ft-long) vessel, however, Plan 10 wave heights were slightly larger than existing conditions. Results also indicated that the smaller vessels (27- and 30-m-long (90- and 100-ft-long)) moving at greater speeds produced the largest wave heights in the harbor for existing conditions as well as for Plans 9 and 10. Greater wave heights occurred for existing conditions for southbound vessels entering the St. Clair River, whereas larger wave heights occurred for Plans 9 and 10 for northbound vessels leaving the St. Clair River.

Sediment-tracer patterns downstream of the harbor were monitored during the conduct of the experiments. The typical movement of sediment-tracer material and subsequent deposits along the shoreline downstream of the harbor are shown in Photo 157 for existing conditions. Visual observations revealed similar patterns in this vicinity for Plans 9 and 10. The deposits, however, were not as heavy since less material moved around the structure in the same time frame of the experiments.

Typically, when structures are installed along a shoreline, accretion occurs on the updrift side, and erosion normally occurs downdrift of the structure. The model was constructed as a fixed bed, and erosion could not be determined. The area immediately south of the harbor, however, currently experiences erosion (as evidenced by the exposure of the steel sheet-pile tie rods). The construction of the proposed improvements probably will not alleviate this condition. Therefore, it may be necessary to nourish this area.

Wave heights for the raised breakwater of Plan 11 indicated it was not effective in reducing wave heights in the harbor for typical storm-wave conditions (1.22-m (4.0-ft) waves). For 2.07-m (6.8-ft) wave conditions, however, Plan 11 resulted in wave-height reductions ranging from 0.03 to 0.15 m (0.1 to 0.5 ft) in the harbor. Of the improvement plans with absorbers installed in the harbor (Plans 12-16), Plan 14 appeared to be the most effective in reducing wave heights in the harbor. Wave heights in the harbor for 1.22-m (4.0-ft) waves were reduced from 0.0 to 0.06 m (0.0 to 0.2 ft). For 2.07-m (6.8-ft) waves, wave heights were reduced from 0.09 to 0.24 m (0.3 to 0.8 ft) in the harbor for Plan 14.

# 7 Conclusions and Recommendations

The existing location of USCG Station, Port Huron, is strategically located to provide search and rescue operations for boaters on lower Lake Huron. An alternative mooring location on the Black River, a tributary of the St. Clair River, increases rescue response times by as much as 20 to 30 min. However, at this existing location, the boat basin is subjected to a dynamic hydraulic flow regime because of the proximity of the entrance to the St. Clair River. Shoaling problems have plagued this site since construction of the boat basin in 1932. Previous studies conducted by the CEU Cleveland and USCG Academy have proposed numerous alternatives to address the shoaling problem including open moorings, offshore breakwaters, and relocating the station. USCG Academy (1974) even stated,

> "There appears no easy solution from a scientific/engineering standpoint. The situation that exists does not appear solvable by any known method of boat basin configuration. Any alteration of the southern end of the north-south breakwater could cause the creation of eddies and vortex shedding that does not now exist."

USCG Academy (1974) appears to have well predicted the current state, as numerous eddies and vortex shedding can now be observed at the site in the vicinity of the basin opening. The flow separation is particularly problematic at this location because it encourages sedimentation and transport of finer grained sediments into the boat basin.

The present study, however, does not hold to the belief that modifying the boat basin configuration will not ease the shoaling problem. The physical model tests conducted for this study indicate that an extension and shift of the east breakwall lakeward will keep longshore-sediment transport on a deeper slope away from the boat basin and closer to the stronger currents further from shore. Tracer studies in the physical model showed a marked reduction in deposited tracer inside the boat basin with the extended and shifted breakwall over the existing configuration. In addition, the extended and shifted breakwall reduces wave energy inside the basin by limiting its entrance into the basin.

Based on the results of the physical coastal model investigation reported herein, the following is concluded:

*a.* Existing conditions are characterized by rough and turbulent wave conditions in the harbor. Very confused wave patterns were observed because of reflected wave energy off the vertical walls in the harbor. Wave heights of 1.19 m (3.9 ft) were obtained for typical storm conditions (1.22-m (4.0-ft) incident waves); and wave heights of 1.8 m (5.9 ft) were obtained for extreme storm-wave conditions (2.68-m (8.8-ft) incident waves).

*b.* Sediment-tracer experiments for existing conditions revealed that shoaling of the harbor entrance will occur for all hydrodynamic conditions studied (i.e., both wave directions, both swls, and both riverflow and no flow conditions).

*c.* Experimental results for the initial improvement plans (Plans 1-8) indicated that the breakwater configurations of Plans 6 and 7 were optimum with regard to wave protection in the harbor and the prevention of shoaling in the entrance channel. Results obtained for these configurations were used as a basis for subsequent experiments.

*d.* The Plans 9 and 10 breakwater configurations resulted in significant improvements in wave conditions in the harbor relative to existing conditions. Considering all hydrodynamic conditions, wave heights in the harbor were reduced from 31 to 71 percent for Plan 9 and from 34 to 67 percent for Plan 10.

*e.* Sediment-tracer experiments conducted for Plans 9 and 10 revealed that the Plan 9 configuration will provide slightly more shoaling protection of the harbor entrance than that of Plan 10. Both plans, however, are a significant improvement over existing conditions.

*f.* The breakwater configurations of Plans 9 and 10 will have no adverse impacts on wave-induced current patterns and magnitudes in the vicinity of the harbor.

*g.* Boat wakes for the smaller vessel (27-m- (90-ft-) long) vessel moving at greater speeds resulted in greater wave heights in the harbor for existing conditions as well as Plans 9 and 10. For this vessel, however, wave heights were significantly reduced for Plans 9 and 10 versus existing conditions. The Plan 9 configuration resulted in wave heights slightly less than those of Plan 10.

*h.* The breakwater configurations of Plans 9 and 10 will have no adverse impacts on sediment patterns and subsequent deposits along the shoreline downstream of the harbor.

*i.* Of the improvement plans consisting of a raised breakwater (Plan 11) and wave absorbers installed in the harbor (Plans 12-16), the absorber of Plan 14 appeared optimum in reducing wave heights in the harbor.

Based on the model results discussed above (namely items *d* through *g*), Plan 9 is recommended for implementation because it provides the best improvement in wave conditions and reduced shoaling over the existing conditions and other plans evaluated.

# References

Bottin, R. R., Jr., and Chatham, C. E., Jr. (1975). "Design for wave protection, flood control, and prevention of shoaling, Cattaraugus Creek Harbor, New York; Hydraulic model investigation," Technical Report H-75-18, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Civil Engineering Unit (CEU), Cleveland. (1991). "Port Huron station shoaling study," U.S. Coast Guard Civil Engineering Unit, Cleveland, OH.

Giles, M. L., and Chatham, C. E., Jr. (1974). "Remedial plans for prevention of harbor shoaling, Port Orford, Oregon; Hydraulic model investigation," Technical Report H-74-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Grant, U.S. (1943). "Waves as a transporting agent," *American Journal of Science* 241, 117-123.

Hough, J. L. (1958). *Geology of the Great Lakes.* University of Illinois Press, Urbana, IL.

Inman, D. L., and Bagnold, R. A. (1963). "Littoral processes." *The sea.* M. N. Hill, ed., Wiley-Interscience, New York, 529-553.

Jensen, R. E. (1983). "Methodology for the calculation of a shallow-water wave climate," WIS Report 8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kraus, N. C., and Rosati, J. D. (1998). "Estimation of uncertainty in coastal sediment budgets at inlets," Coastal Engineering Technical Note IV-16, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lillycrop, W. J., Parson, L. E., and Irish, J. L. (1996). "Development and operation of the SHOALS Airborne Lidar Hydrographic System." *SPIE: Laser remote sensing of natural waters from theory to practice* 2964, 26-37.

Madsen, O. S., and Grant, W. D. (1976). "Sediment transport in the coastal environment," Report No. 209, Ralph M. Parsons Laboratory, Massachusetts Institute of Technology, Cambridge, MA.

Meyer-Peter, E., and Muller, R. (1948). "Formulas for bed-load transport." *Proceedings, International Association of Hydraulic Structure Research.* Stockholm.

Nielsen, P. (1992). *Coastal bottom boundary layers and sediment transport—advanced series on ocean engineering.* Volume 4, World Scientific, New Jersey.

Noda, E. K. (1972). "Equilibrium beach profile scale-model relationship," *Journal Waterways, Harbors, and Coastal Engineering Division,* American Society of Civil Engineers 98 (WW4), 511-528.

Reinhard, R. D., Driver, D. B., and Hubertz, J. M. (1991). "Hindcast wave information for the Great Lakes: Lake Huron," WIS Report 26, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Resio, D. T., and Vincent, C. E. (1977). "Design wave information for the Great Lakes; Report 4, Lake Huron," Technical Report H-76-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Shore Protection Manual. (1984). 4th ed., 2 Vols, U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, U.S. Government Printing Office, Washington, DC.

Stevens, J. C., et al. (1942). "Hydraulic models," *Manuals of Engineer Practice No. 25,* American Society of Civil Engineers, New York.

U.S. Army Corps of Engineers (USACE). (1992). Coastal Littoral Transport, Engineer Manual 1110-2-1502, U.S. Army Corps of Engineers, Washington, DC.

U.S. Coast Guard (USCG) Academy. (1974). "Boat basin sediment accretion study," U.S. Coast Guard Academy, New London, CT.

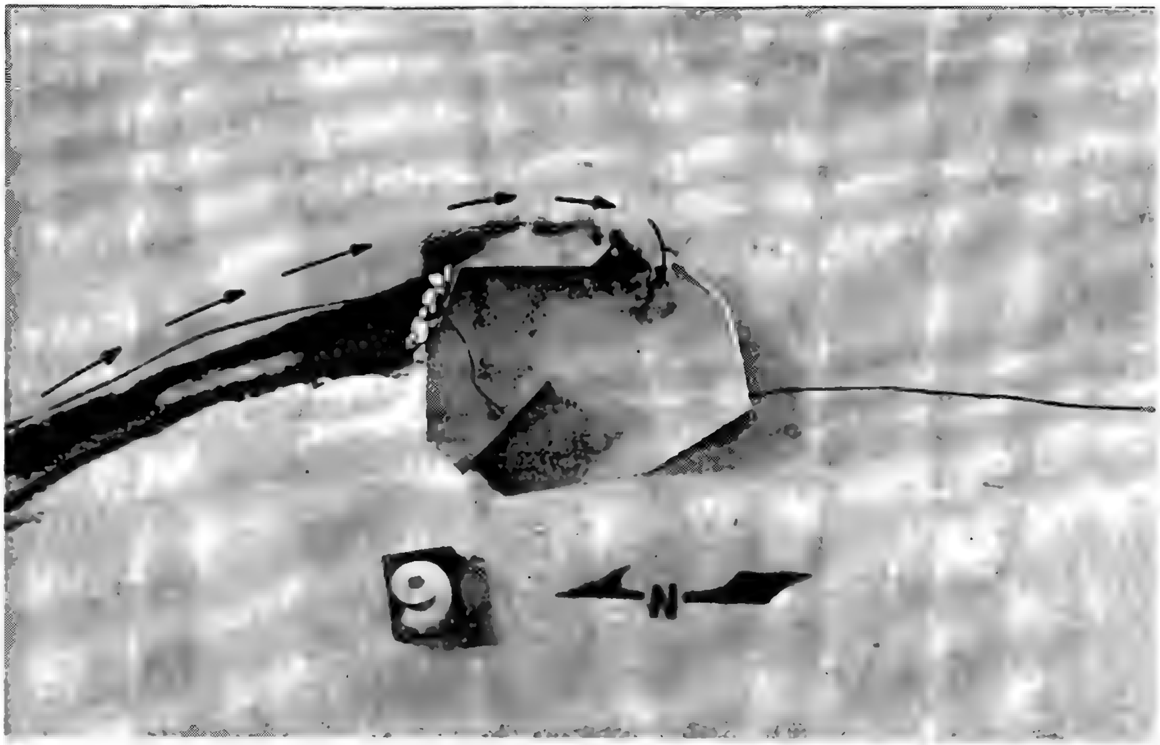



Photo 1. General movement of tracer material and subsequent deposits for existing conditions; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = + 1.7 ft (no riverflow conditions)

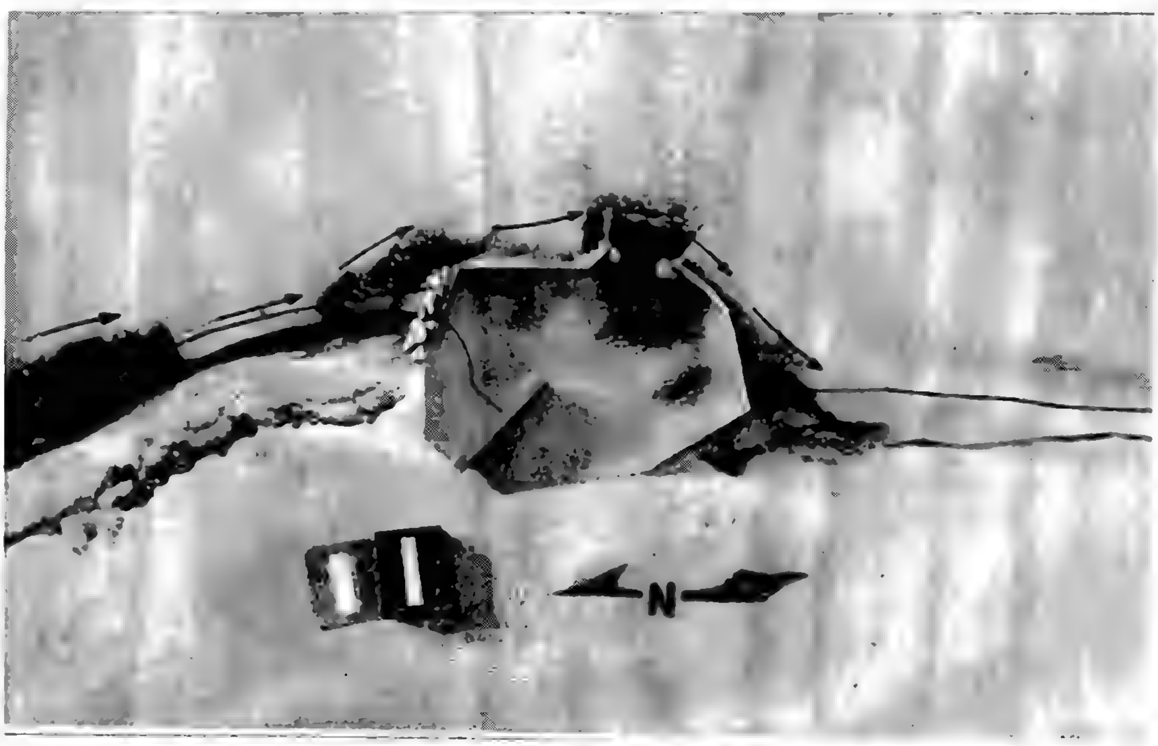



Photo 2. General movement of tracer material and subsequent deposits for existing conditions; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +1.7 ft (no riverflow conditions)

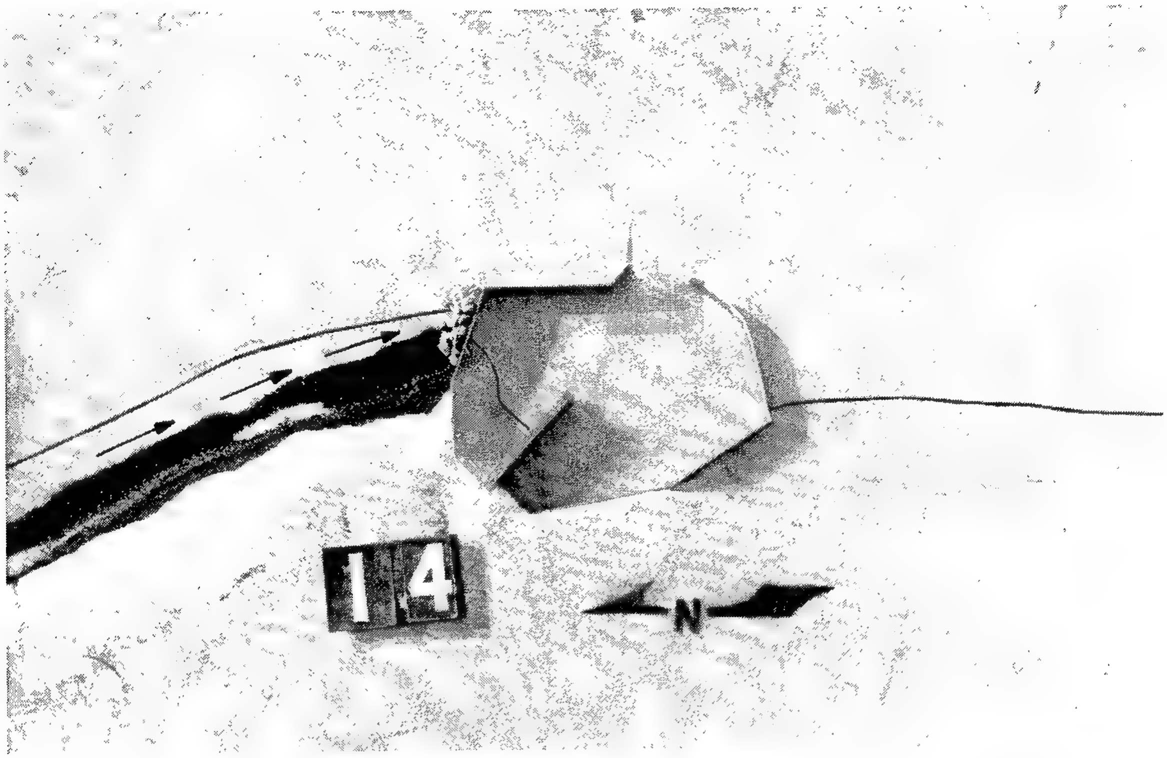



Photo 3. General movement of tracer material and subsequent deposits for existing conditions; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (no riverflow conditions)

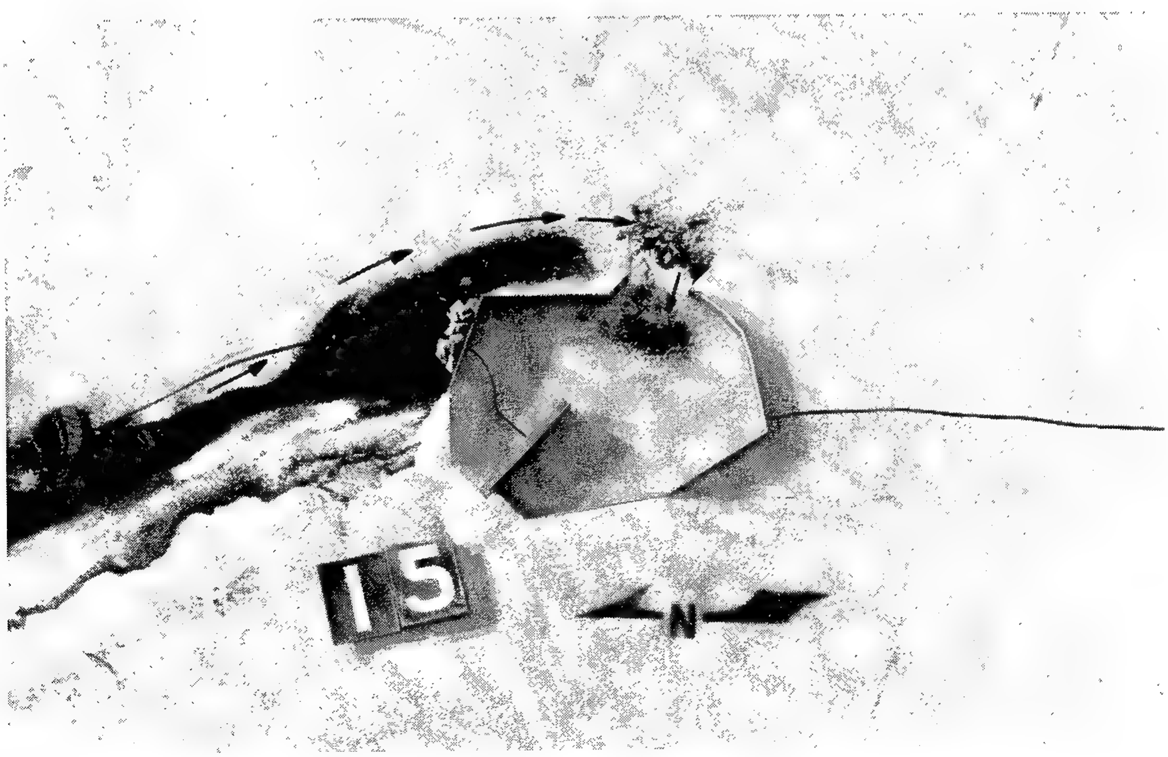



Photo 4. General movement of tracer material and subsequent deposits for existing conditions; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +3.5 ft (no riverflow conditions)

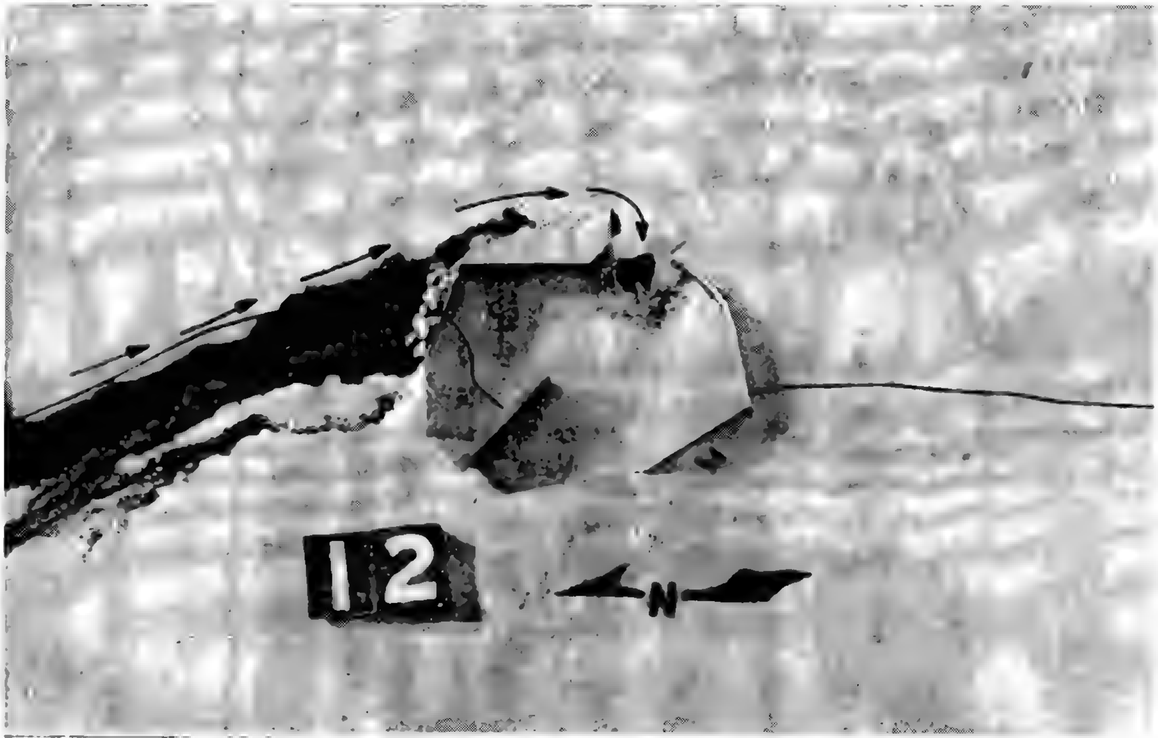



Photo 5. General movement of tracer material and subsequent deposits for existing conditions; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +1.7 ft (with riverflow conditions)

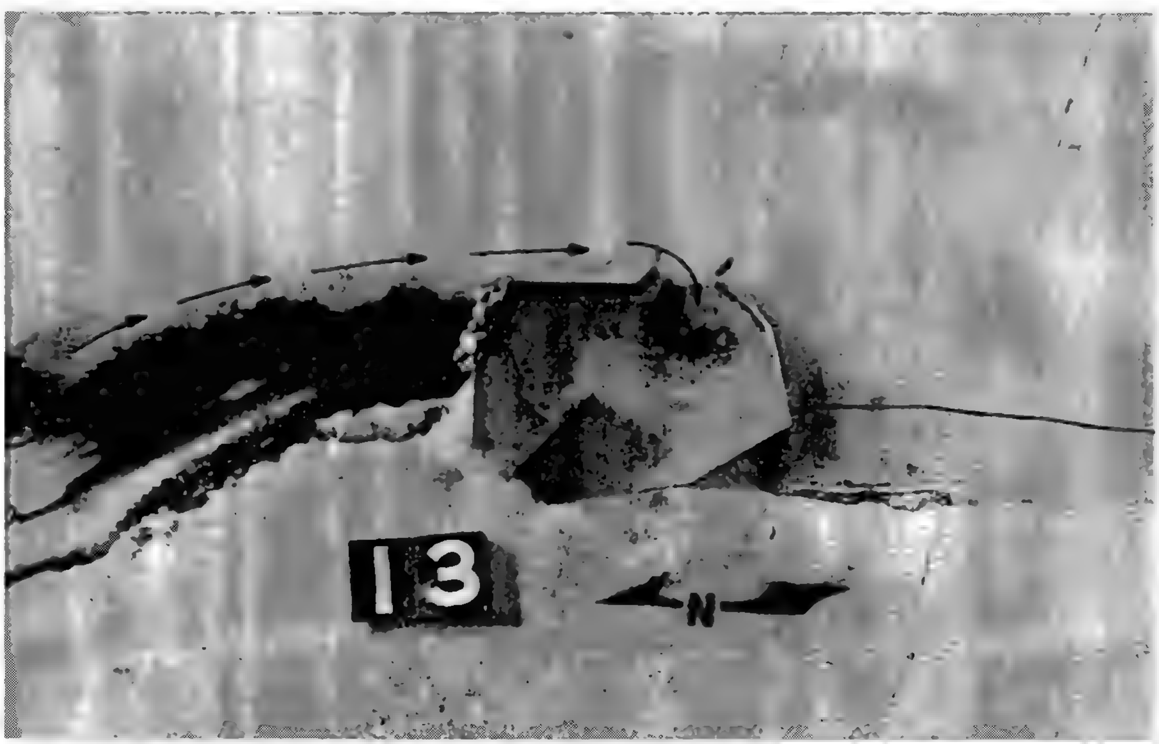



Photo 6. General movement of tracer material and subsequent deposits for existing conditions; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9 sec, 6.8-ft waves run for 5 min from 11 deg; swl = +1.7 ft (with riverflow conditions)

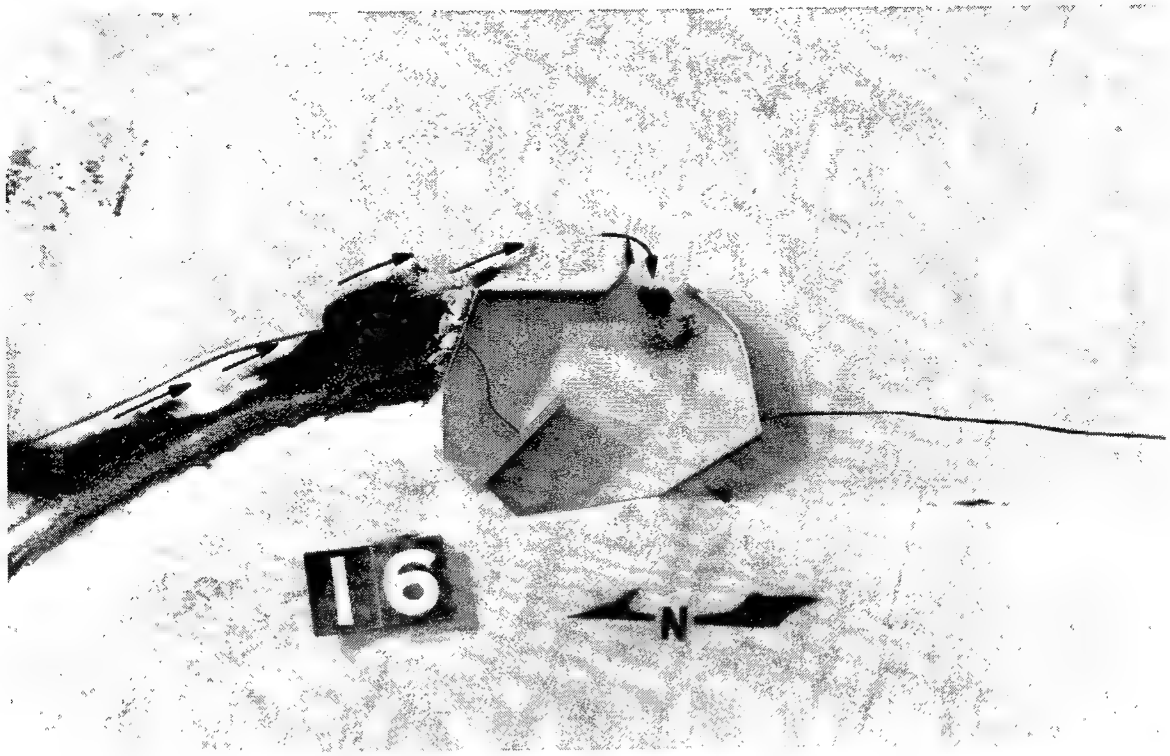



Photo 7. General movement of tracer material and subsequent deposits for existing conditions; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

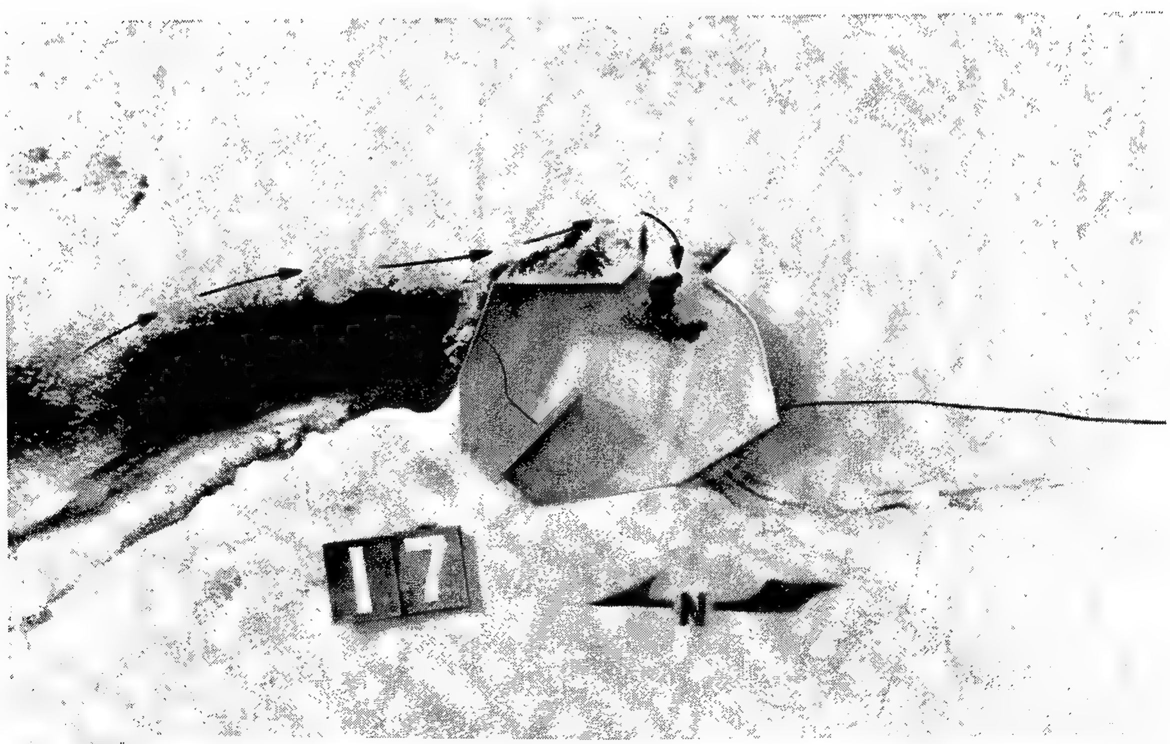



Photo 8. General movement of tracer material and subsequent deposits for existing conditions; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

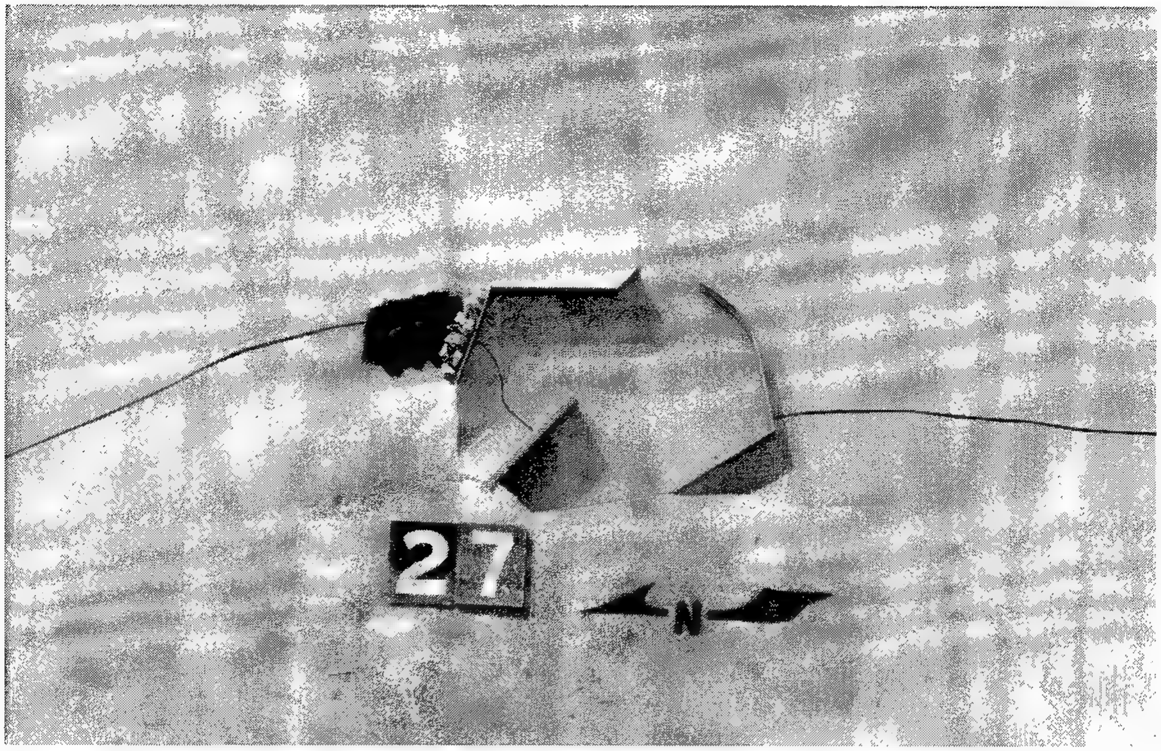



Photo 9. Placement of tracer material prior to experiments from 59 deg

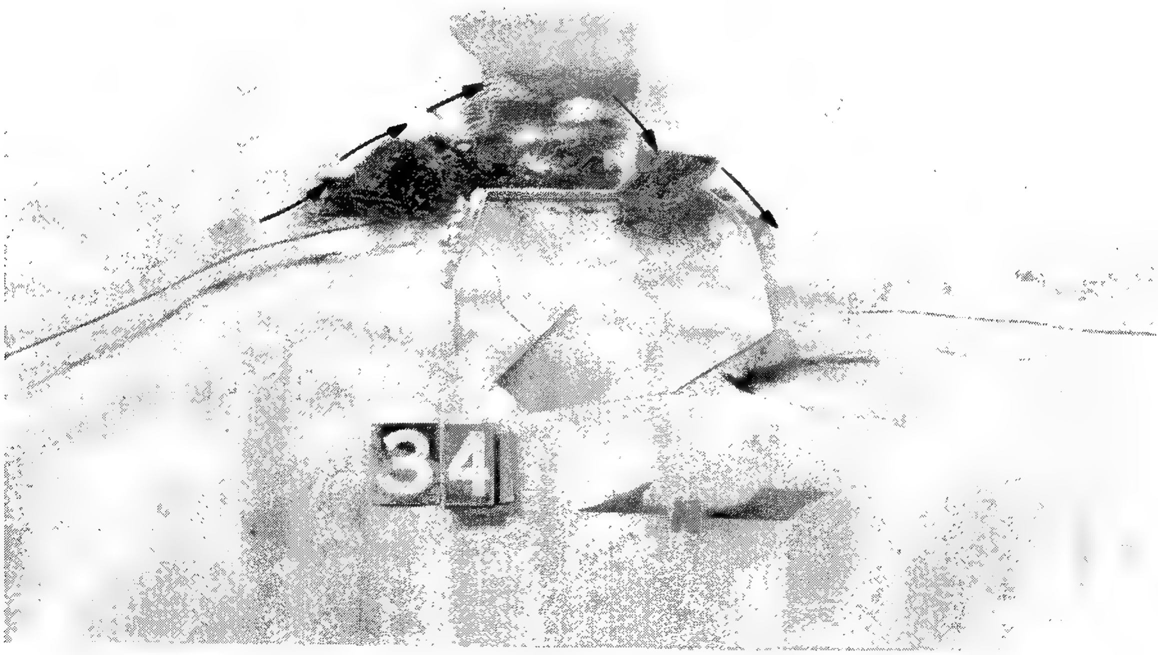



Photo 10. General movement of tracer material and subsequent deposits for existing conditions; 5.0-sec, 4.0-ft waves run for 10 min from 59 deg; swl = +1.7 ft (no riverflow conditions)

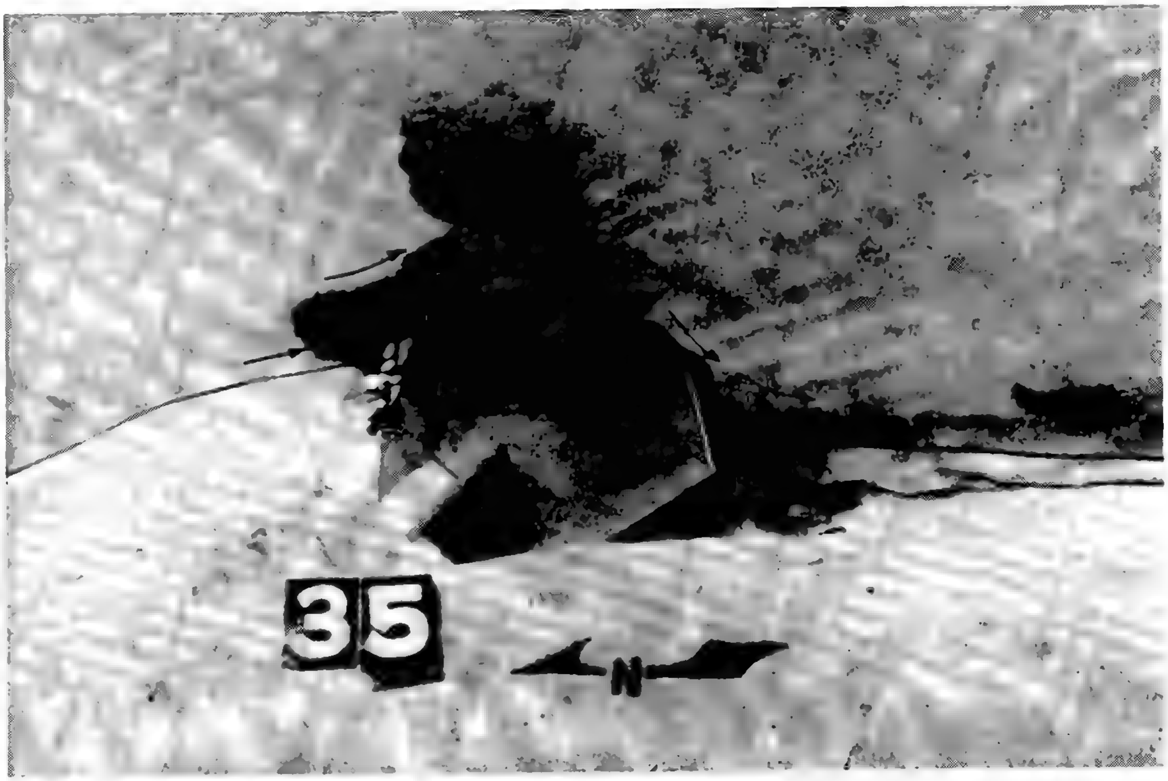



Photo 11. General movement of tracer material and subsequent deposits for existing conditions; 5.0-sec, 4.0-ft waves run for 10 min, and 6.0-sec, 6.1-ft waves run for 5 min from 59 deg; swl = +1.7 ft (no riverflow conditions)

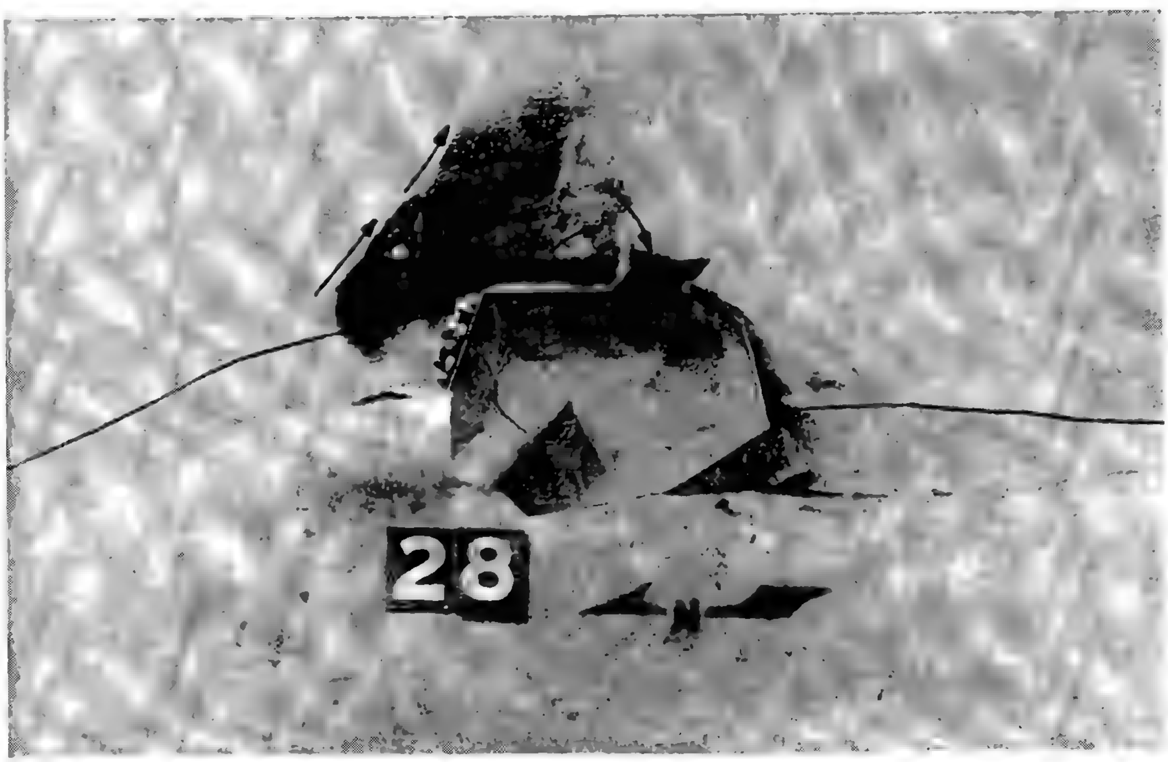



Photo 12. General movement of tracer material and subsequent deposits for existing conditions; 5.0-sec, 4.0-ft waves run for 10 min from 59 deg; swl = +3.5 ft (no riverflow conditions)

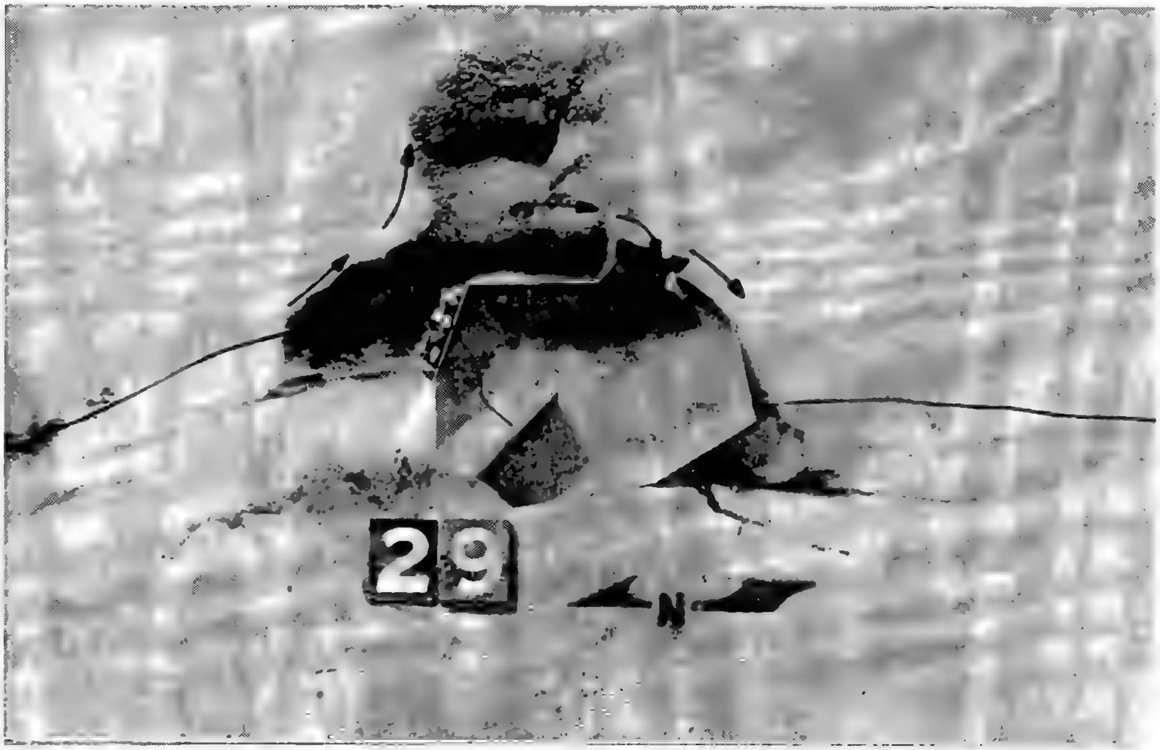



Photo 13. General movement of tracer material and subsequent deposits for existing conditions; 5.0-sec, 4.0-ft waves run for 10 min, and 6.0-sec, 6.1-ft waves run for 5 min from 59 deg; swl = +3.5 ft (no riverflow conditions)


Photo 14. General movement of tracer material and subsequent deposits for existing conditions; 5.0-sec, 4.0-ft waves run for 10 min from 59 deg; swl = +1.7 ft (with riverflow conditions)

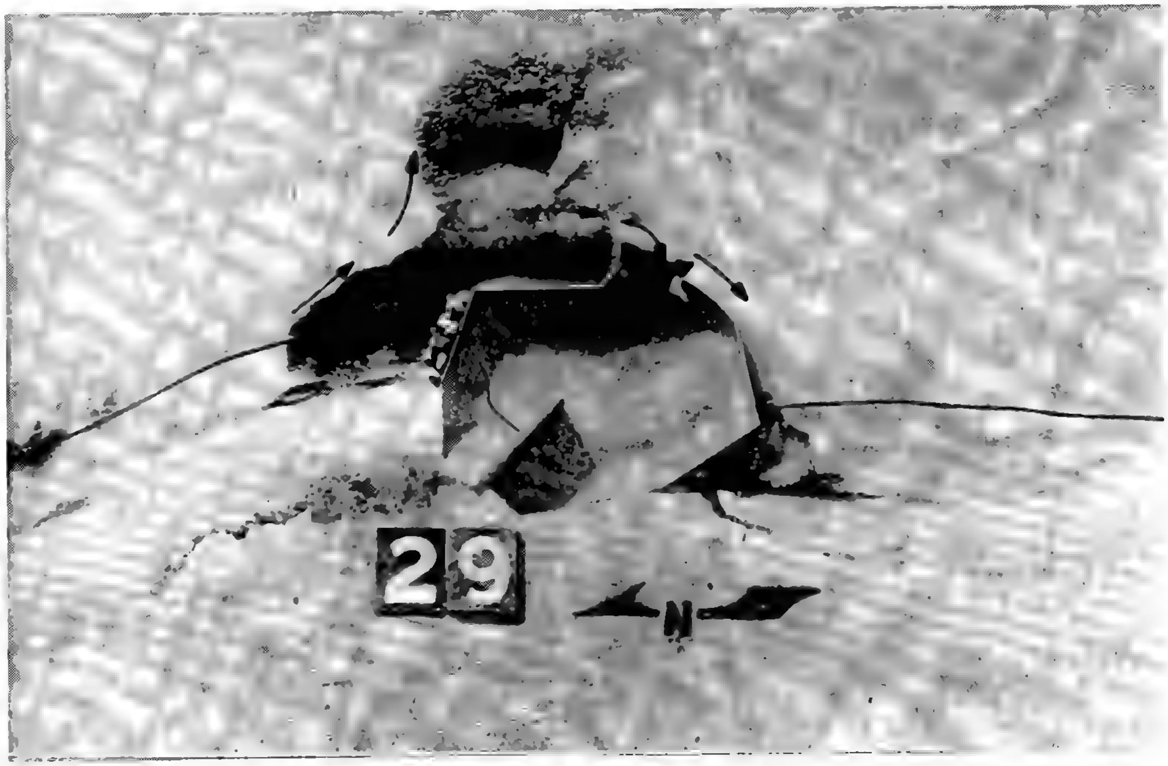



Photo 15. General movement of tracer material and subsequent deposits for existing conditions; 5.0-sec, 4.0-ft waves run for 10 min, and 6.0-sec, 6.1-ft waves run for 5 min from 59 deg; swl = +1.7 ft (with riverflow conditions)

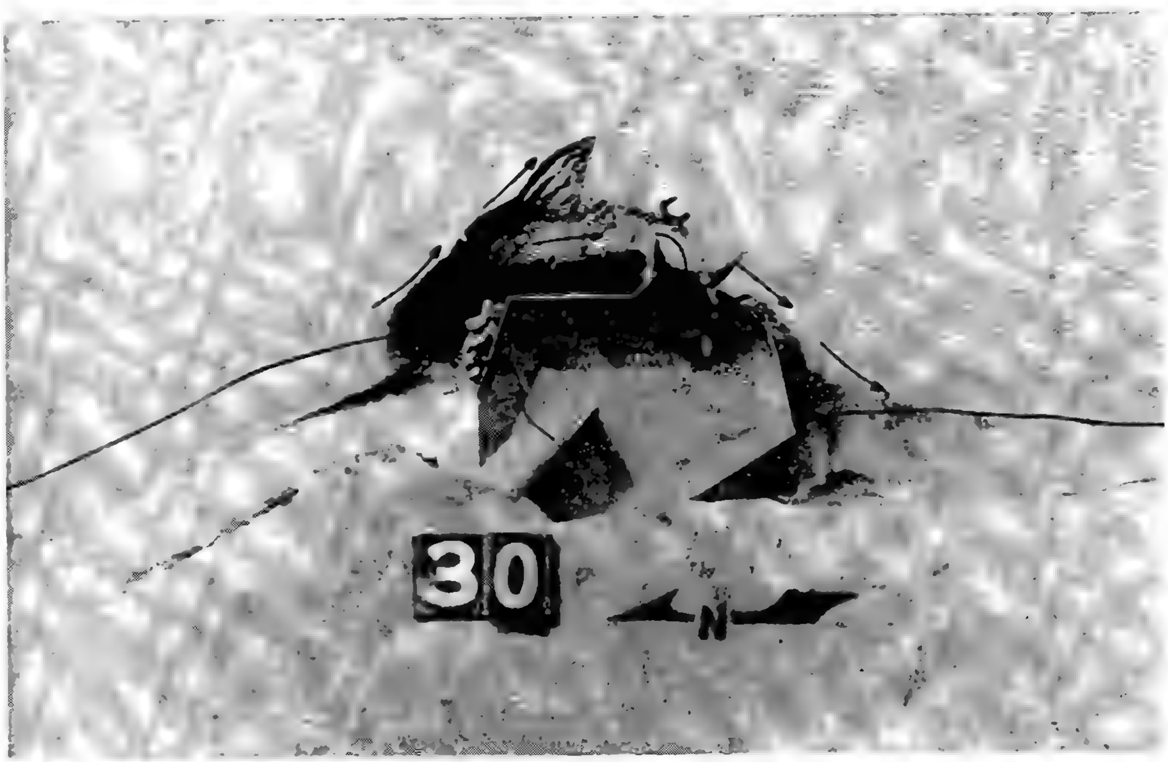



Photo 16. General movement of tracer material and subsequent deposits for existing conditions; 5.0-sec, 4.0-ft waves run for 10 min from 59 deg; swl = +3.5 ft (with riverflow conditions)


Photo 17 General movement of tracer material and subsequent deposits for existing conditions; 5.0-sec, 4.0-ft waves run for 10 min, and 6.0-sec, 6.1-ft waves run for 5 min from 59 deg; swl = +3.5 ft (with riverflow conditions)

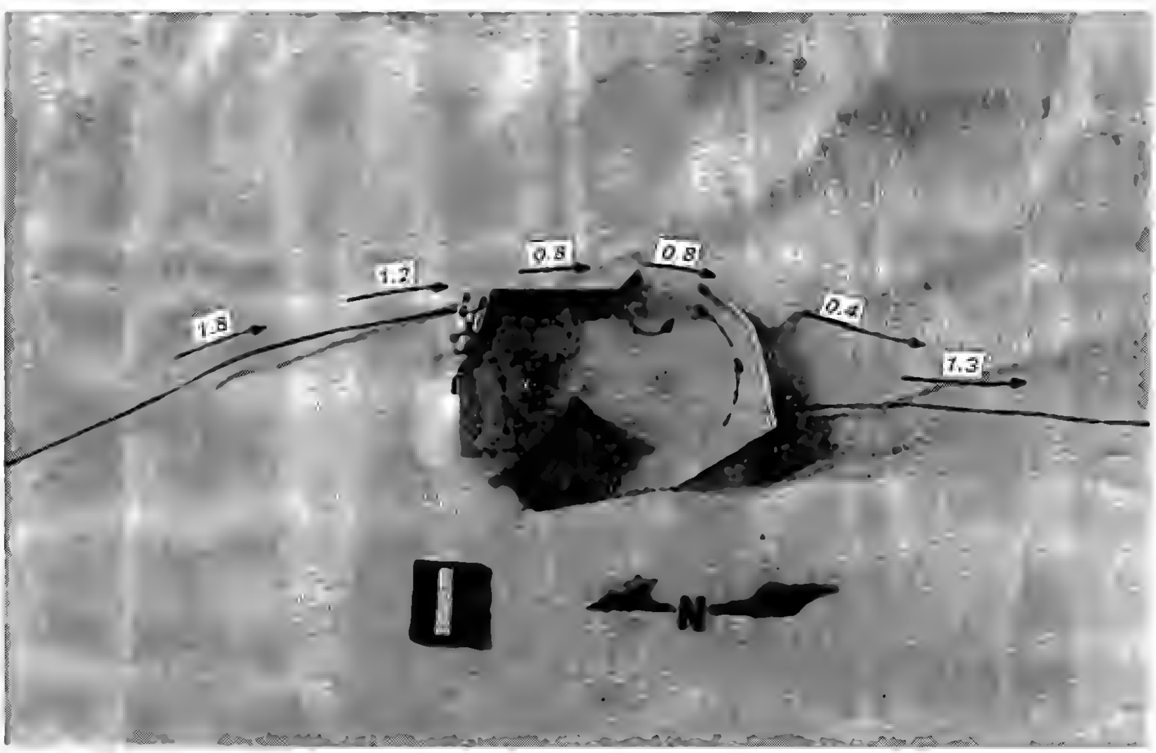



Photo 18 Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 6.0-sec, 4.0-ft waves from 11 deg; swl = +1.7 ft (no riverflow conditions)

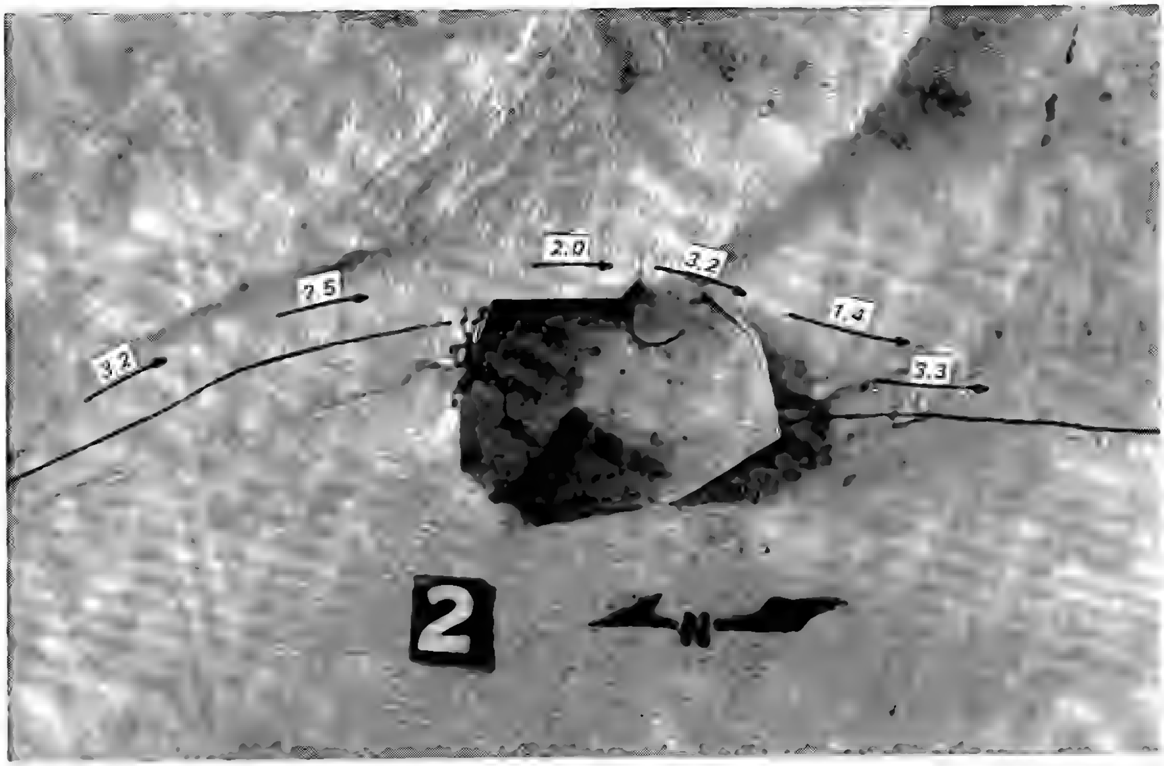



Photo 19 Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions, 8.6-sec, 8.6-ft waves from 11 deg; swl = +1.7 ft (no riverflow conditions)

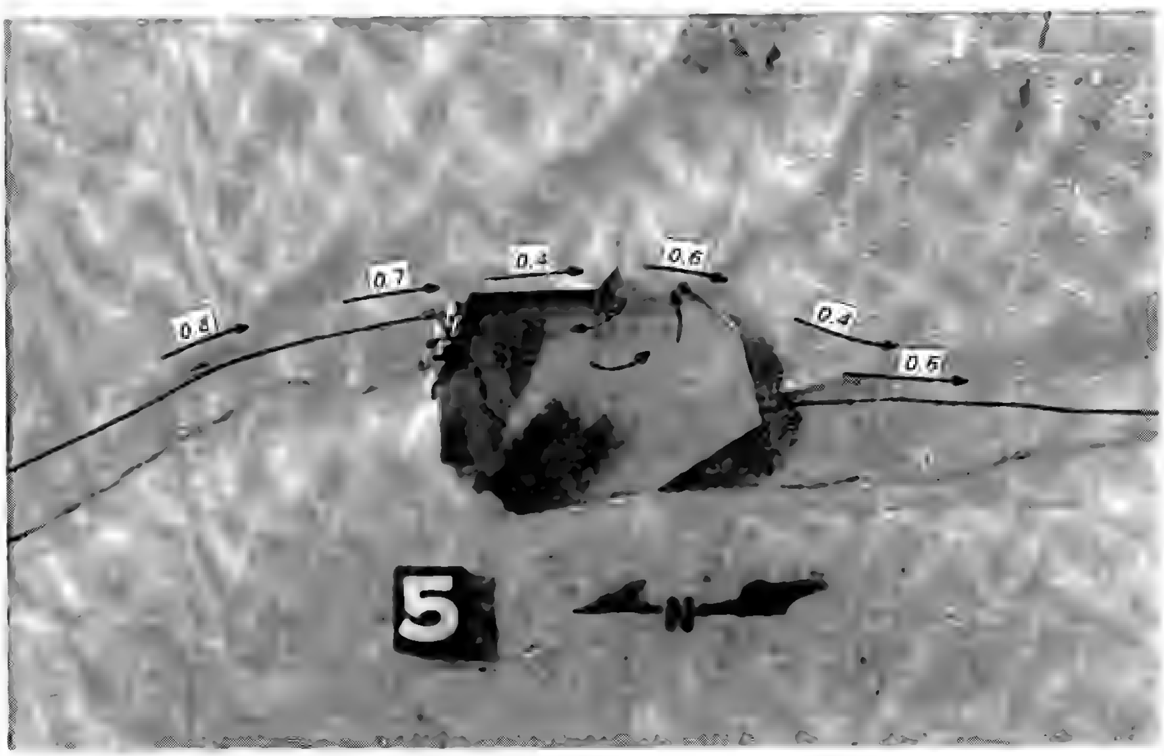



Photo 20 Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions, 6.0-sec, 4.0-ft waves from 11 deg; swl = +3.5 ft (no riverflow conditions)

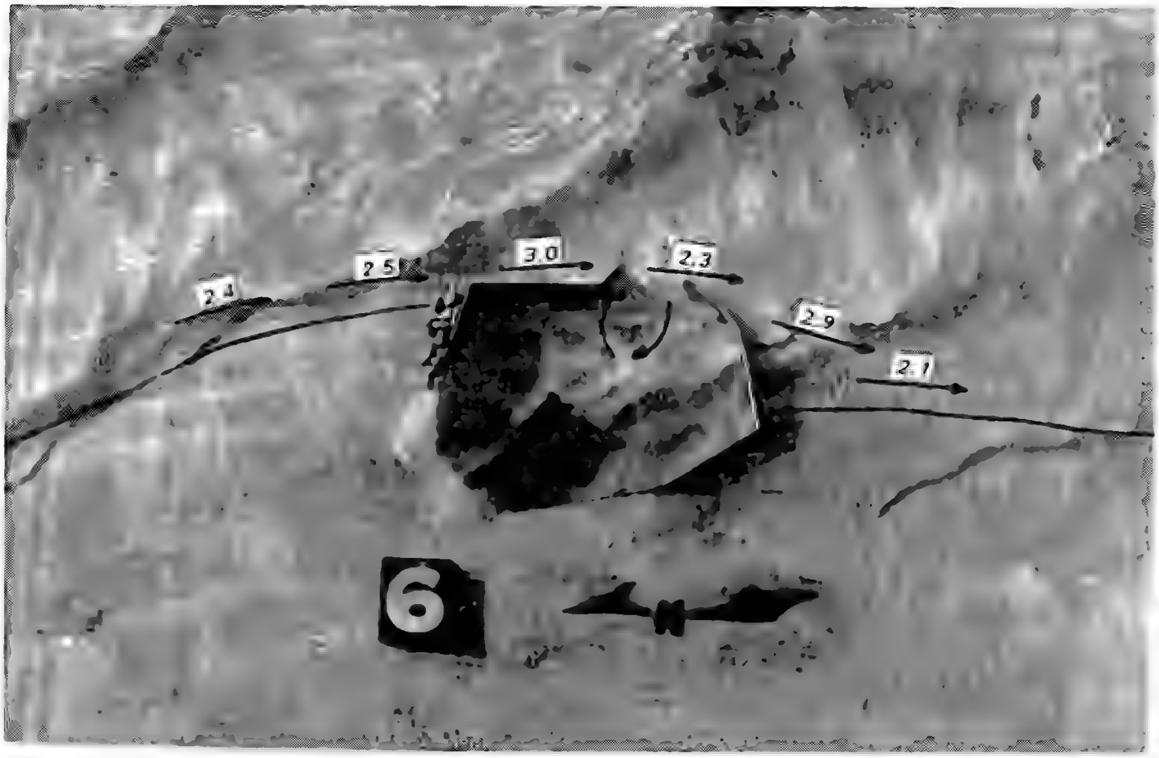



Photo 21 Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions, 8.6-sec, 8.6-ft waves from 11 deg, swl = +3.5 ft (no riverflow conditions)


Photo 22 Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions, 5.0-sec, 4.0-ft waves from 59 deg, swl = +1.7 ft (no riverflow conditions)

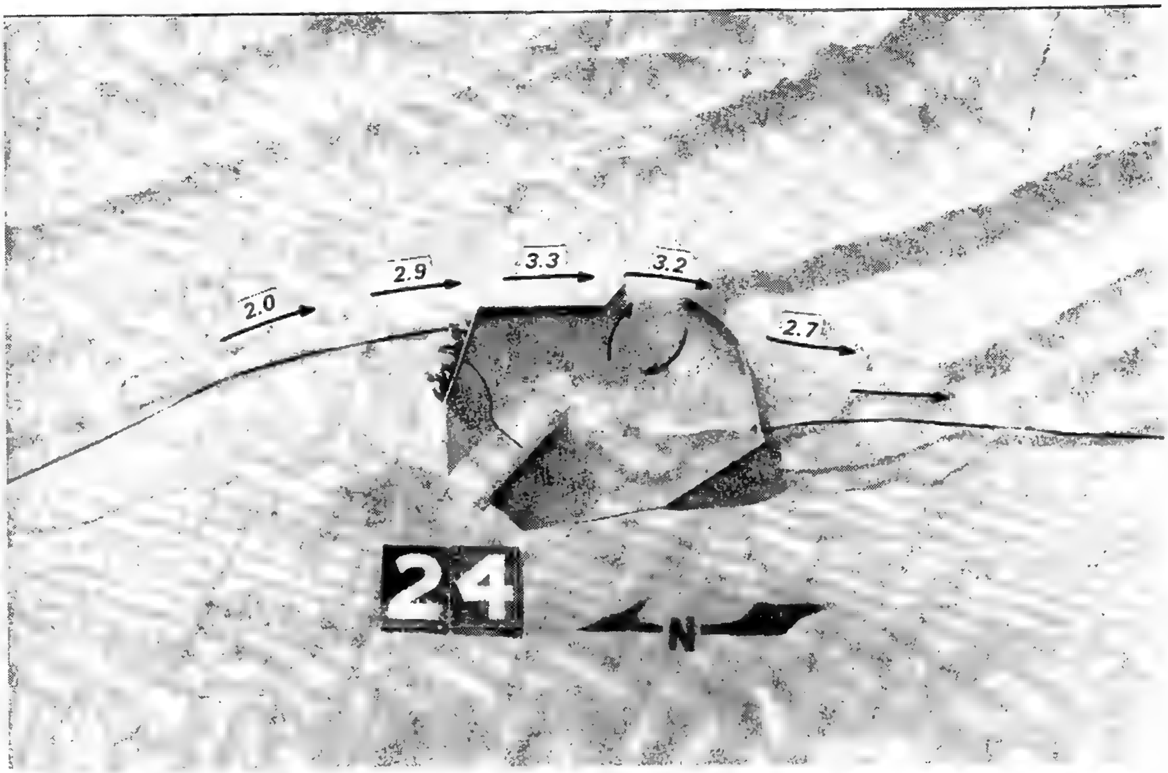



Photo 23. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 6.5-sec, 7.7-ft waves from 59 deg; swl = +1.7 ft (no riverflow conditions)

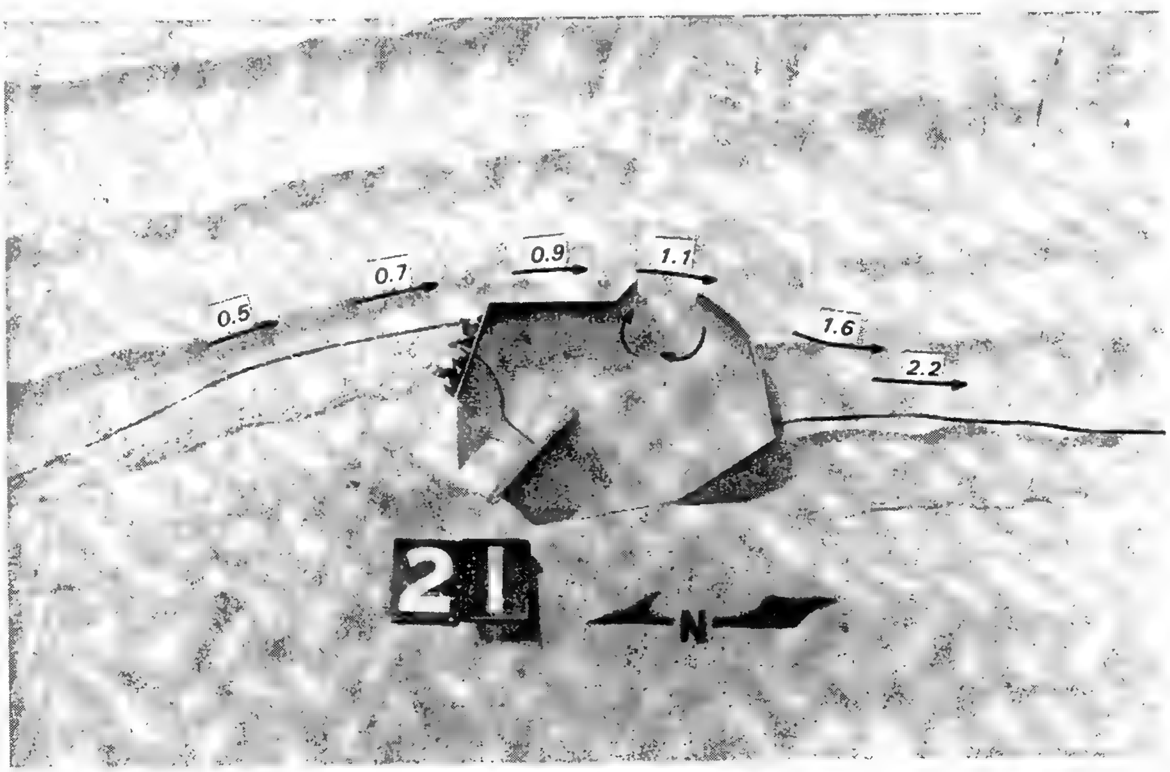



Photo 24. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 5.0-sec, 4.0-ft waves from 59 deg; swl = +3.5 ft (no riverflow conditions)

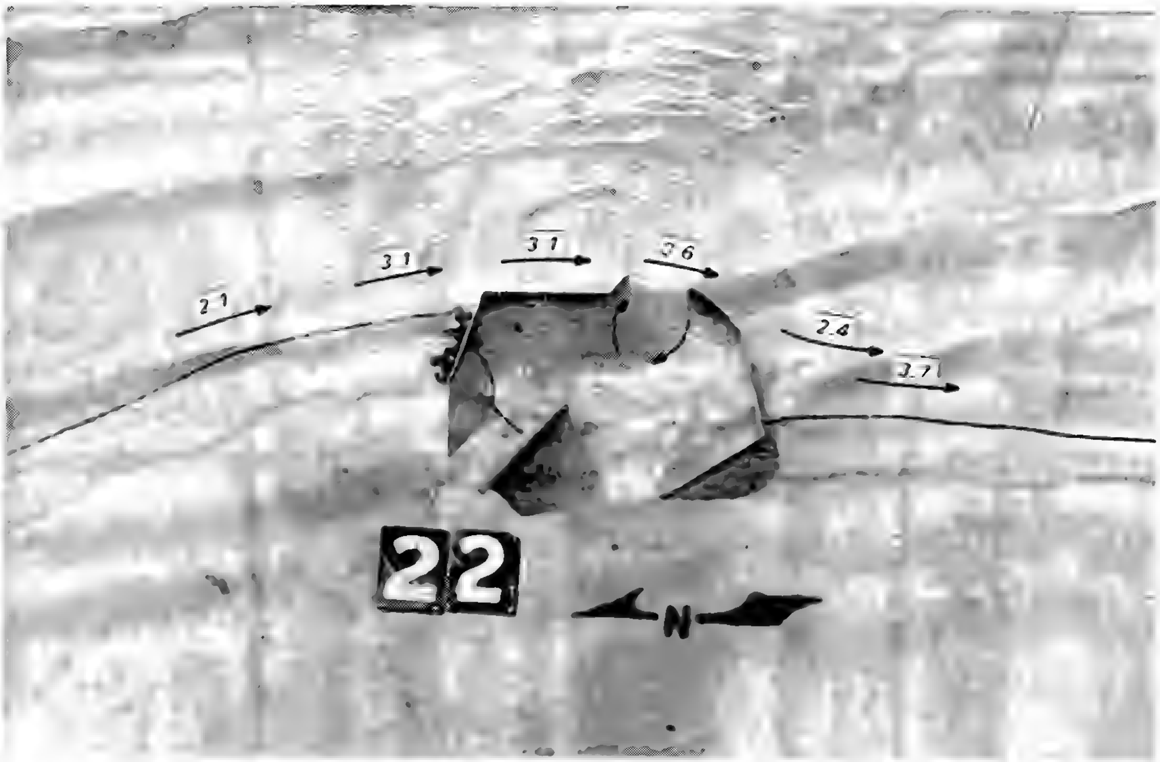



Photo 25 Typical wave patterns current patterns, and current magnitudes (prototype feet per second) for existing conditions, 6.5-sec, 7.7-ft waves from 59 deg, swl = +3.5 ft (no riverflow conditions)

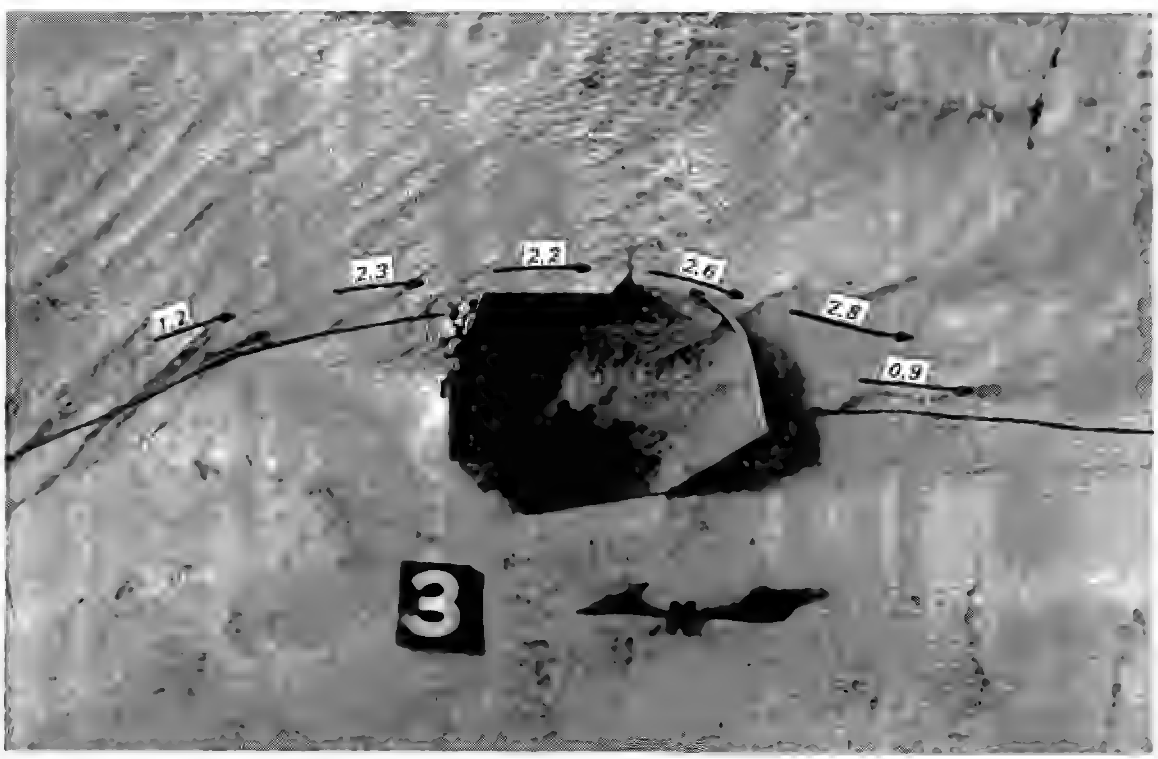



Photo 26 Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 6.0-sec, 4.0-ft waves from 11 deg; swl = +1.7 ft (with riverflow conditions)

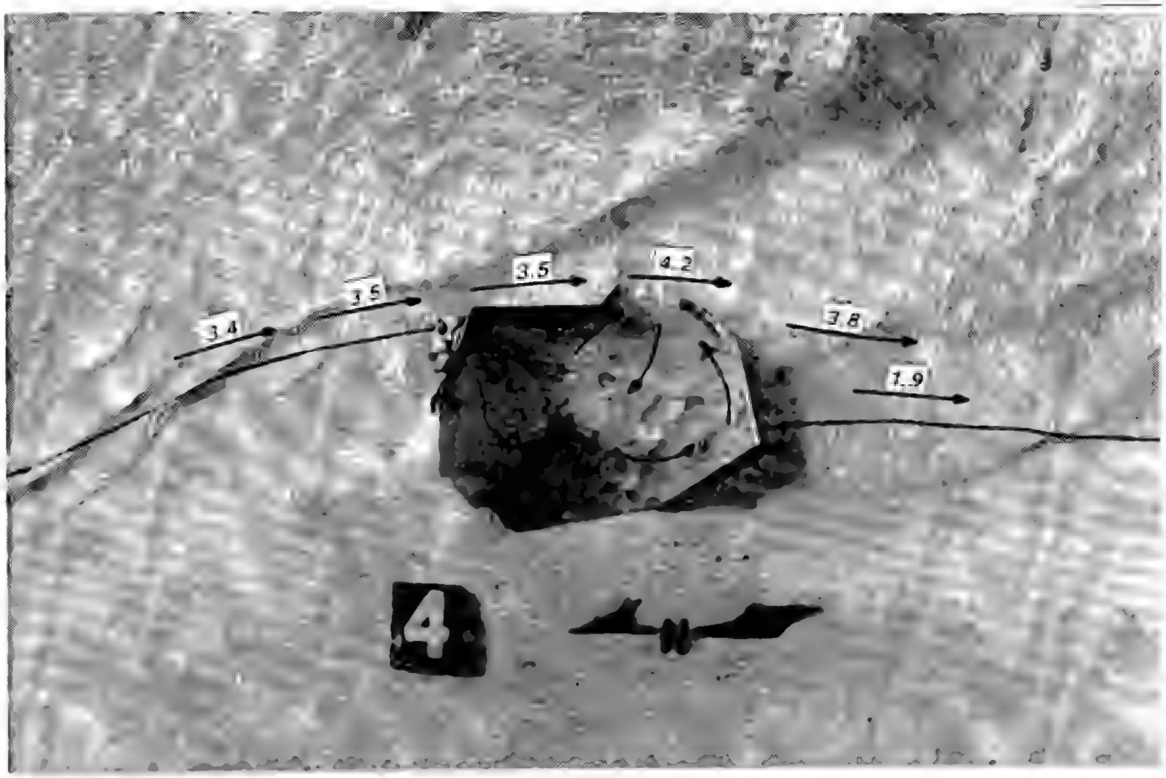



Photo 27 Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions, 8.6-sec, 8.6-ft waves from 11 deg, swl = +1.7 ft (with riverflow conditions)

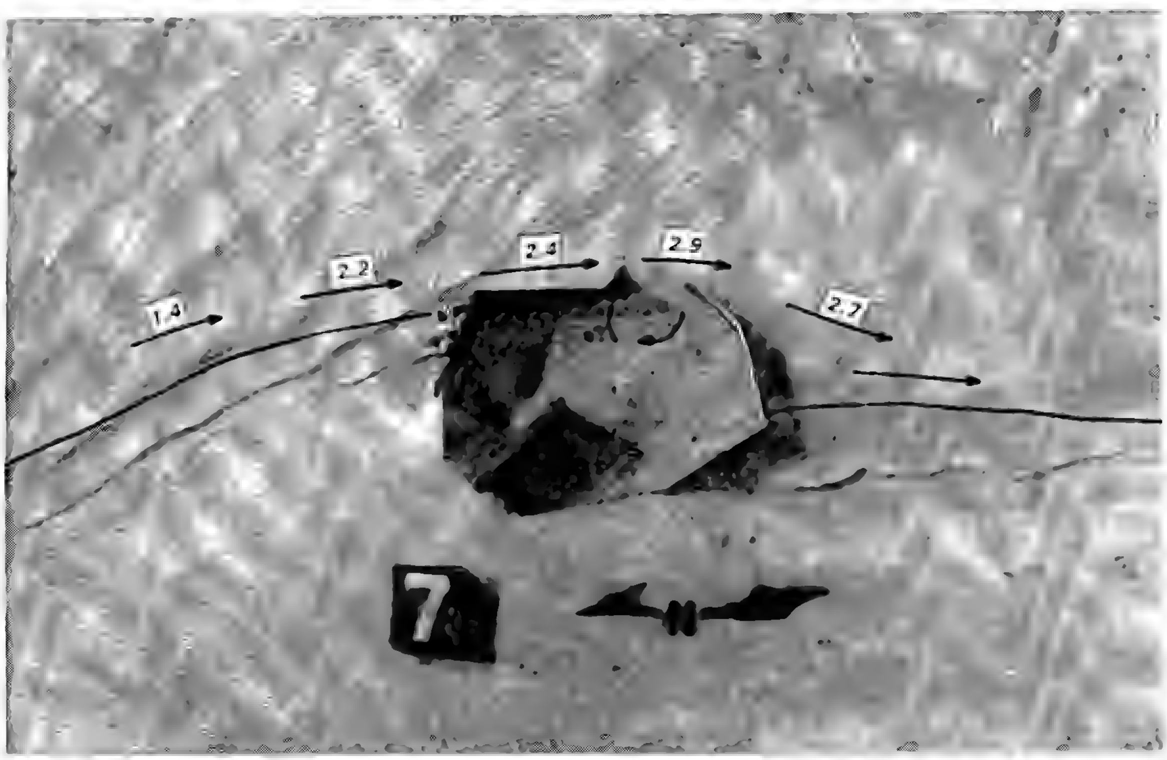



Photo 28 Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions, 6.0-sec, 4.0-ft waves from 11 deg, swl = +3.5 ft (with riverflow conditions)

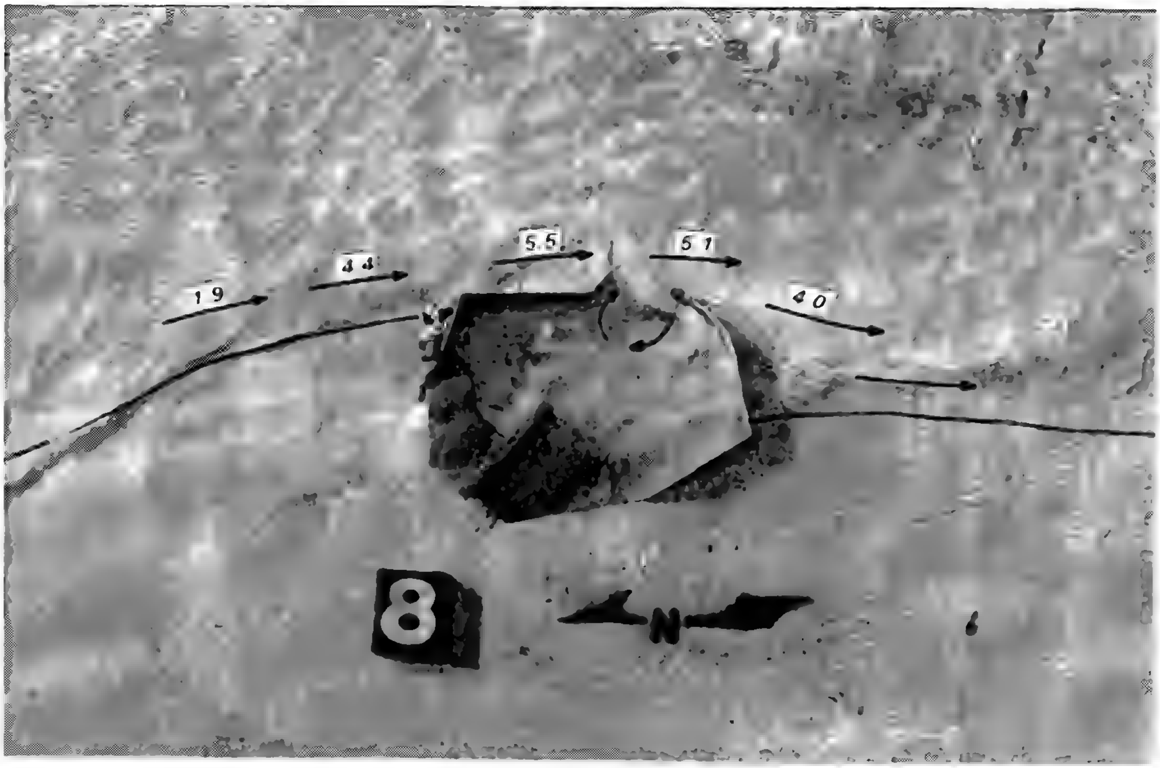



Photo 29. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions, 8.6-sec, 8.6-ft waves from 11 deg, swl = +3.5 ft (with riverflow conditions)

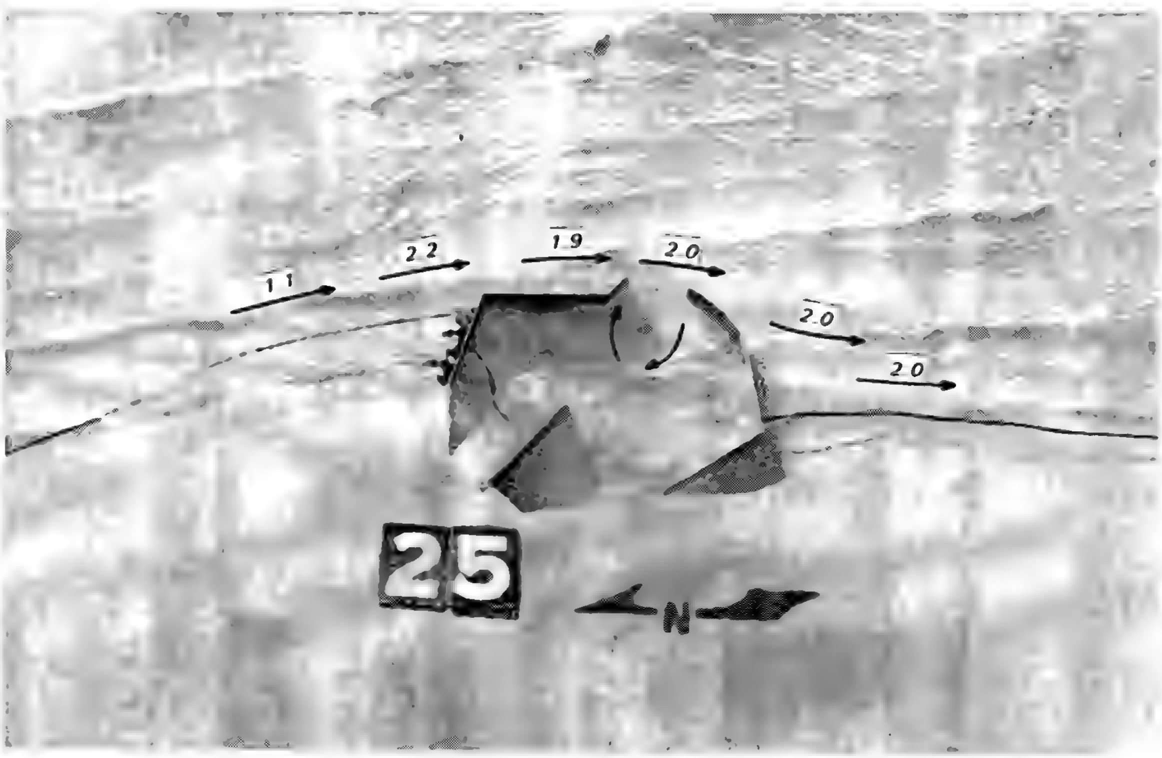



Photo 30. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions, 5.0-sec, 4.0-ft waves from 59 deg, swl = +1.7 ft (with riverflow conditions)

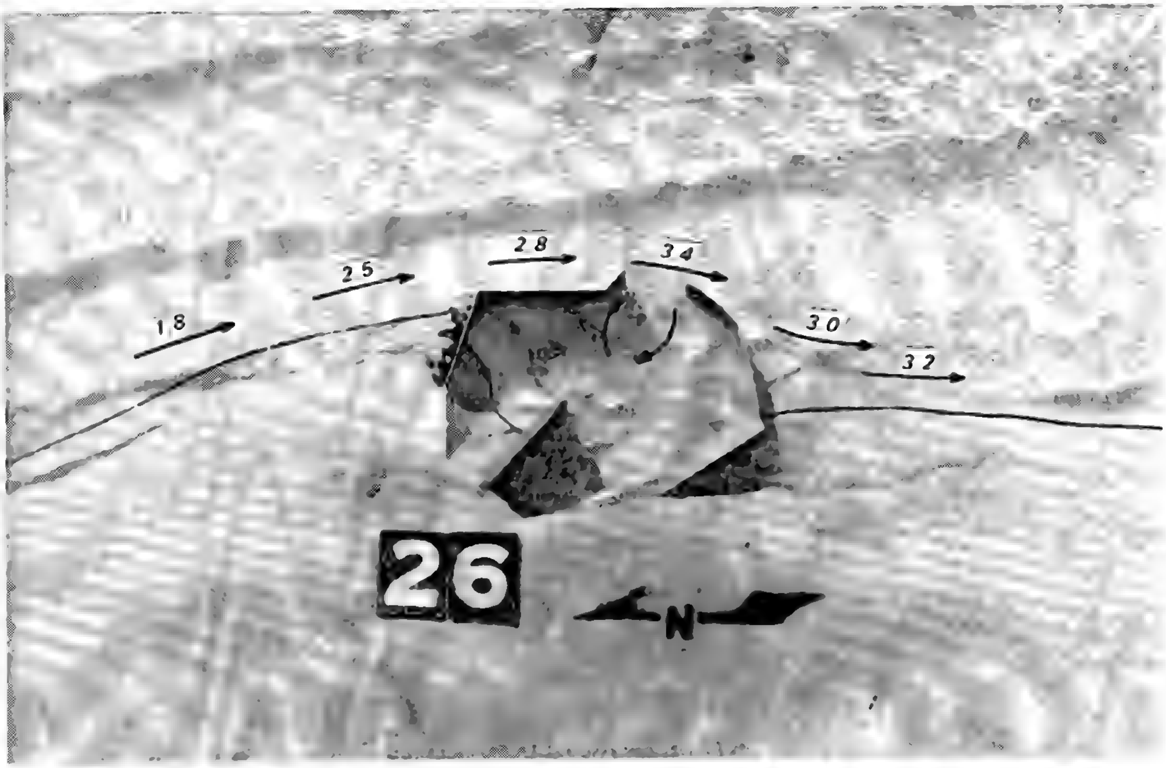



Photo 31. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions, 6.5-sec, 7.7-ft waves from 59 deg, swl = +1.7 ft (with riverflow conditions)

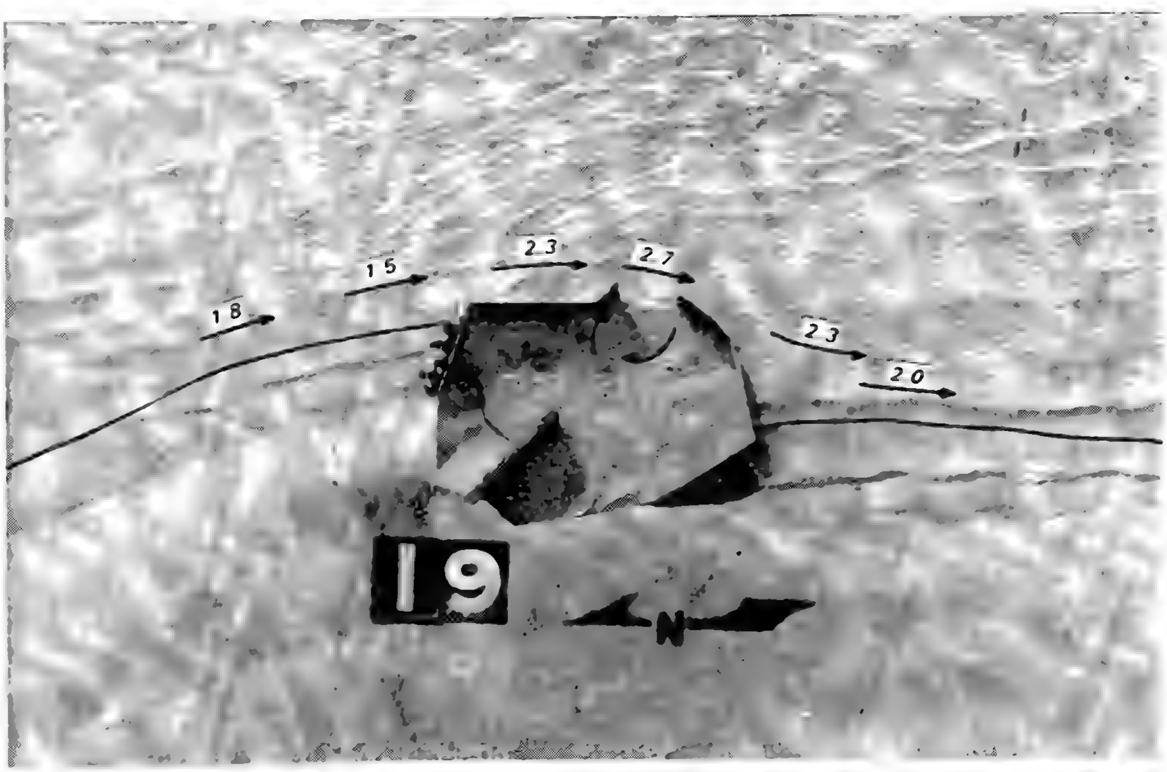



Photo 32. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions, 5.0-sec, 4.0-ft waves from 59 deg, swl = +3.5 ft (with riverflow conditions)

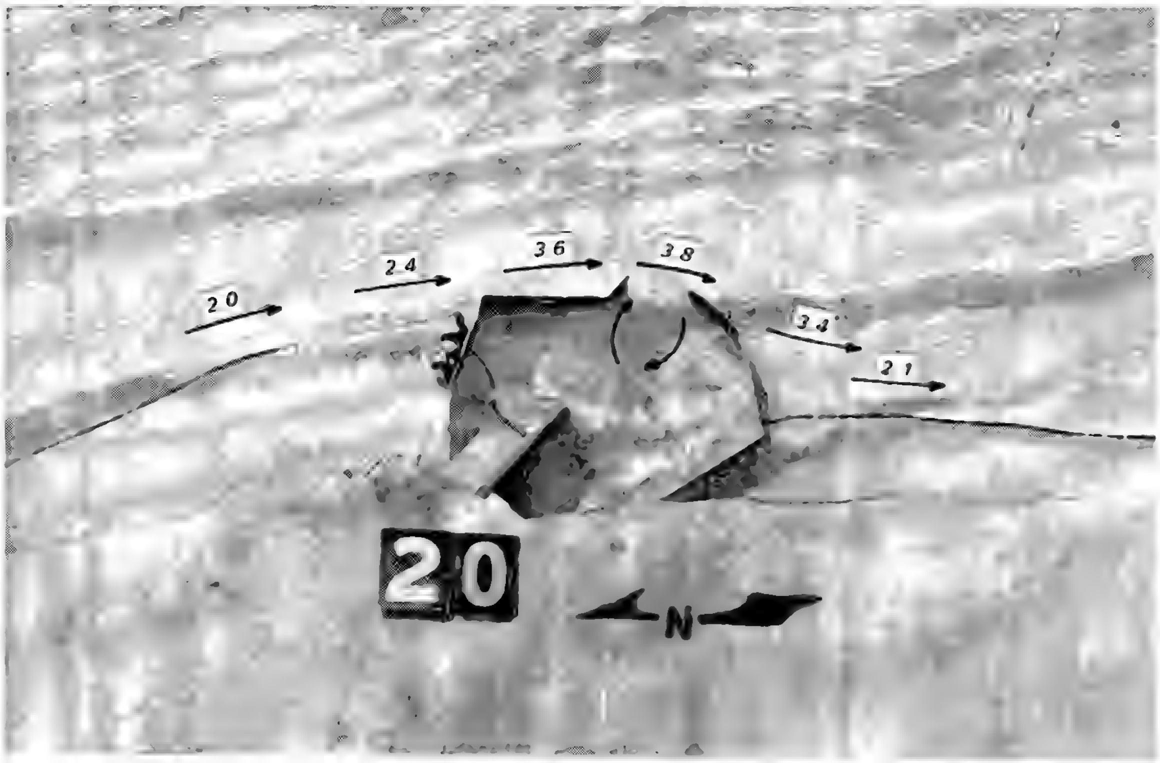



Photo 33 Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 6.5-sec, 7.7-ft waves from 59 deg, swl = +3.5 ft (with riverflow conditions)

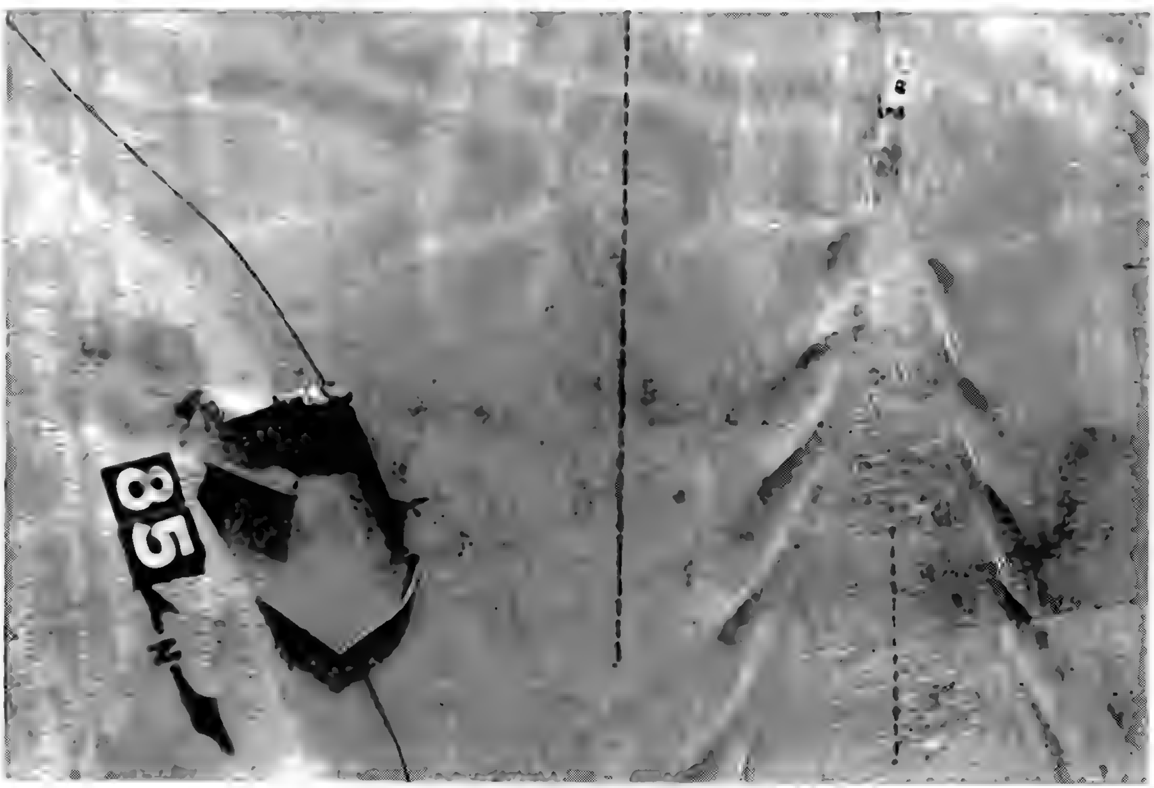



Photo 34. View of 27-m-long (90-ft-long) speedboat leaving St Clair River for existing conditions

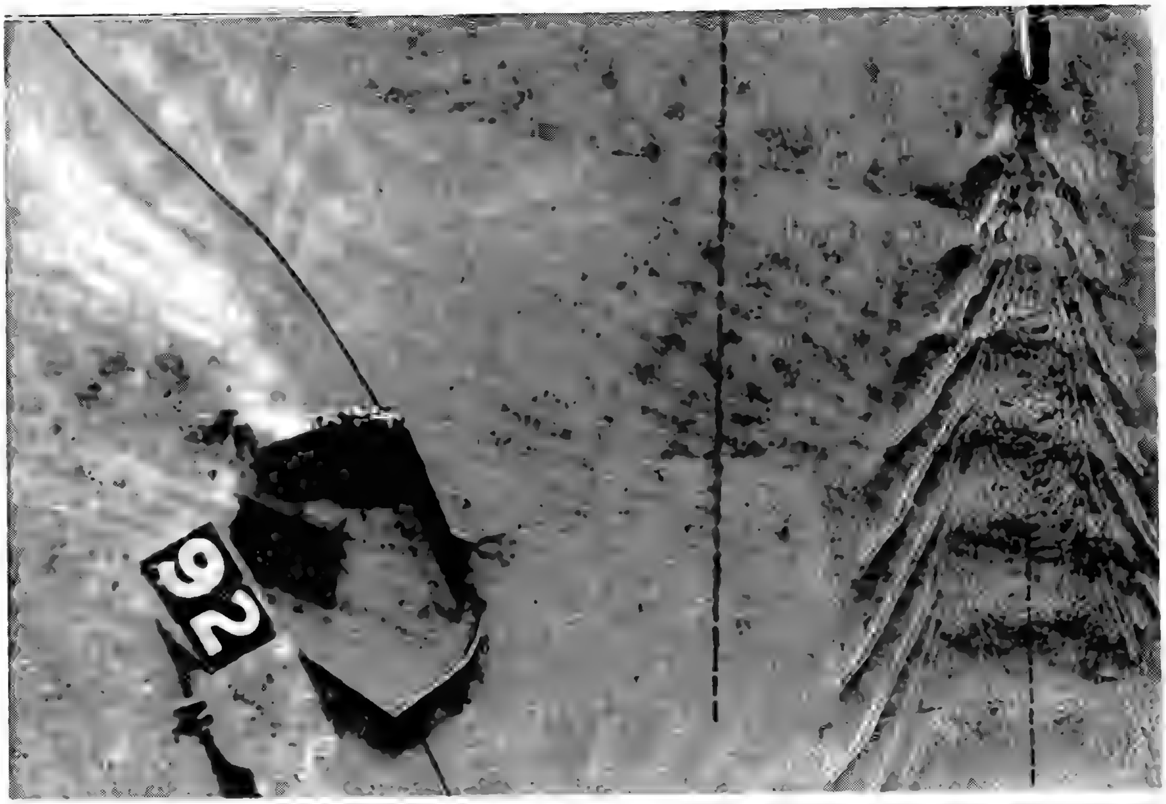



Photo 35 View of 30-m-long (100-ft-long) cabin cruiser leaving St Clair River for existing conditions

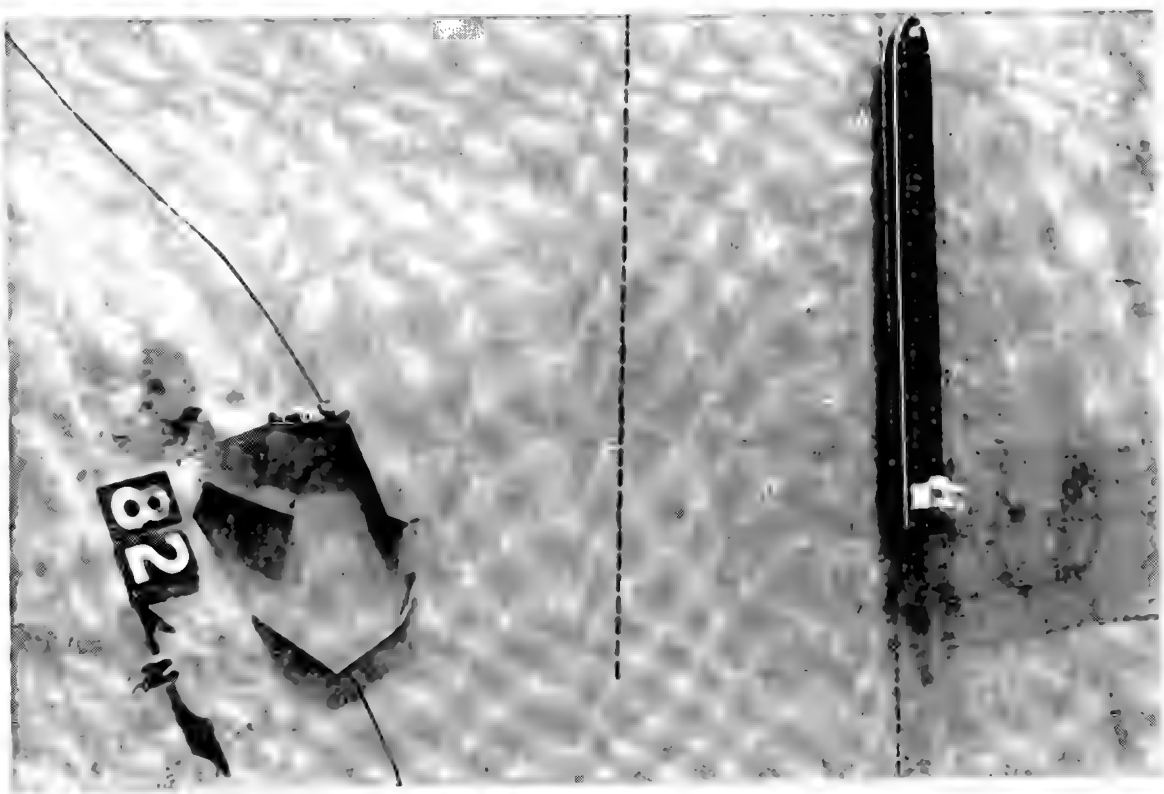



Photo 36. View of 183-m-long (600-ft-long) ore carrier leaving St Clair River for existing conditions

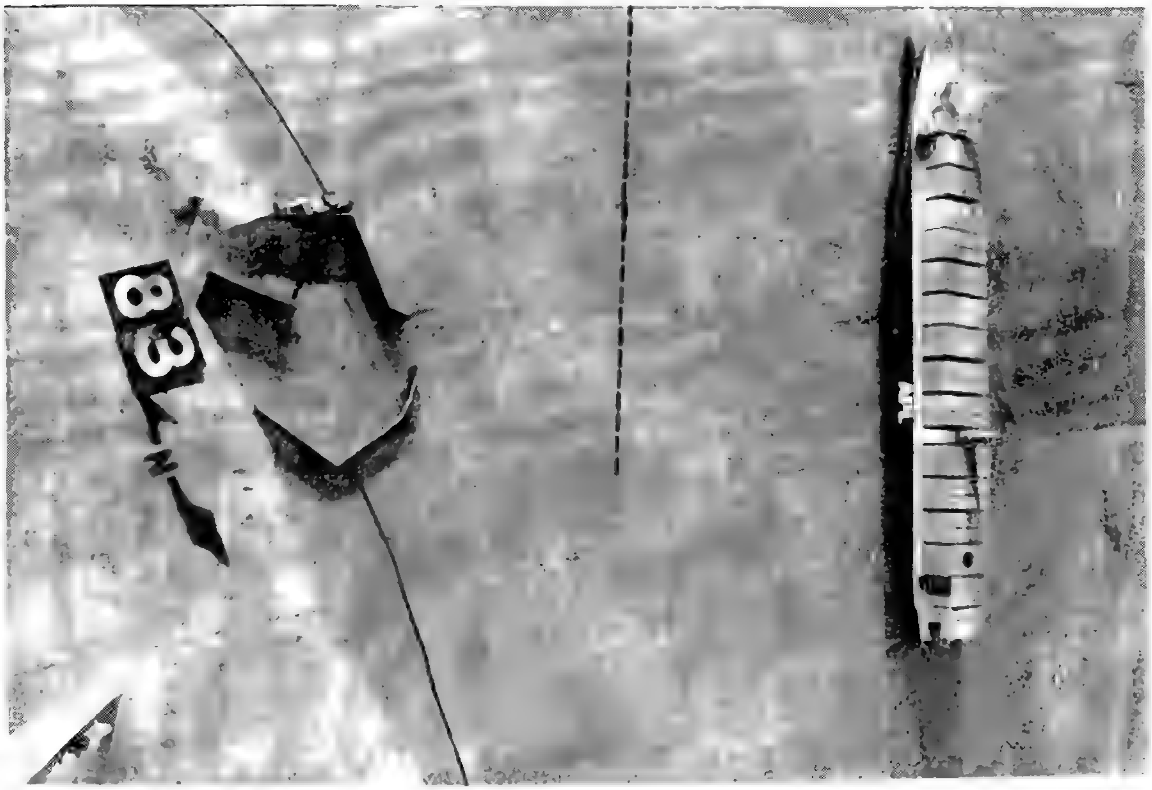



Photo 37. View of 210-m-long (690-ft-long) container vessel leaving St. Clair River for existing conditions


Photo 38. General movement of tracer material and subsequent deposits for Plan 1; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

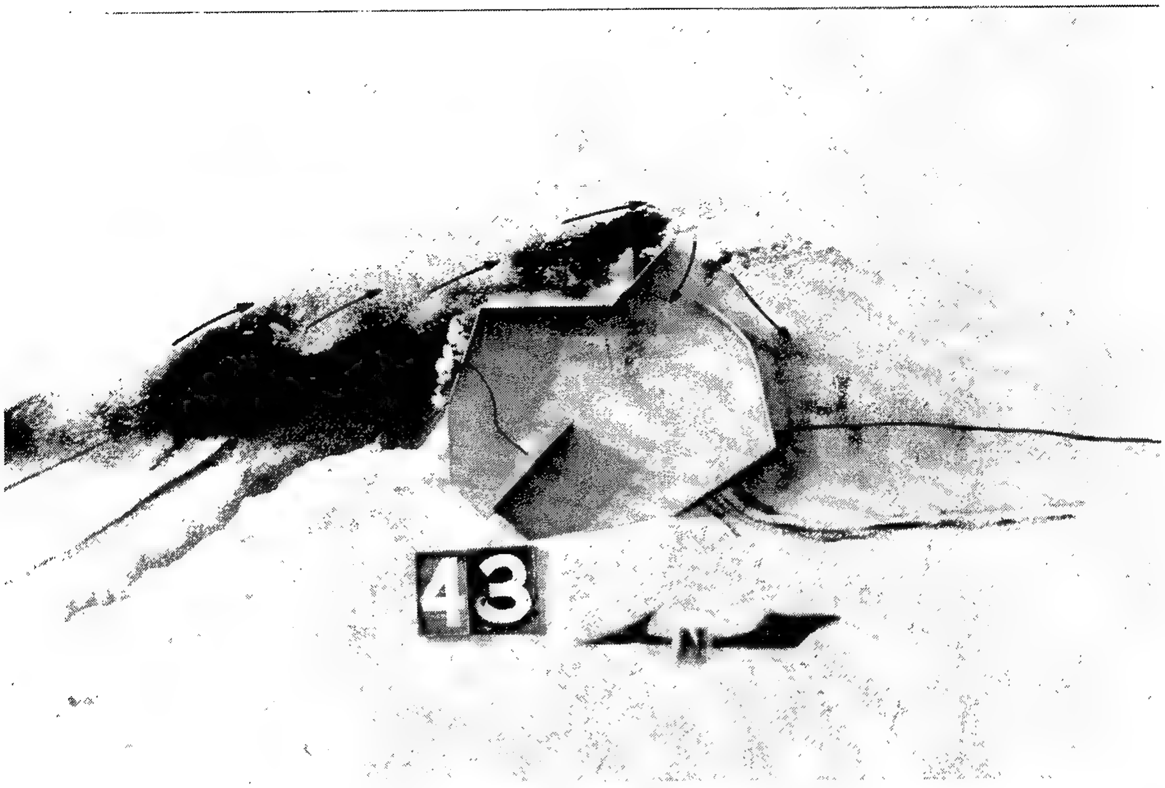



Photo 39. General movement of tracer material and subsequent deposits for Plan 1; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves runt for 5 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

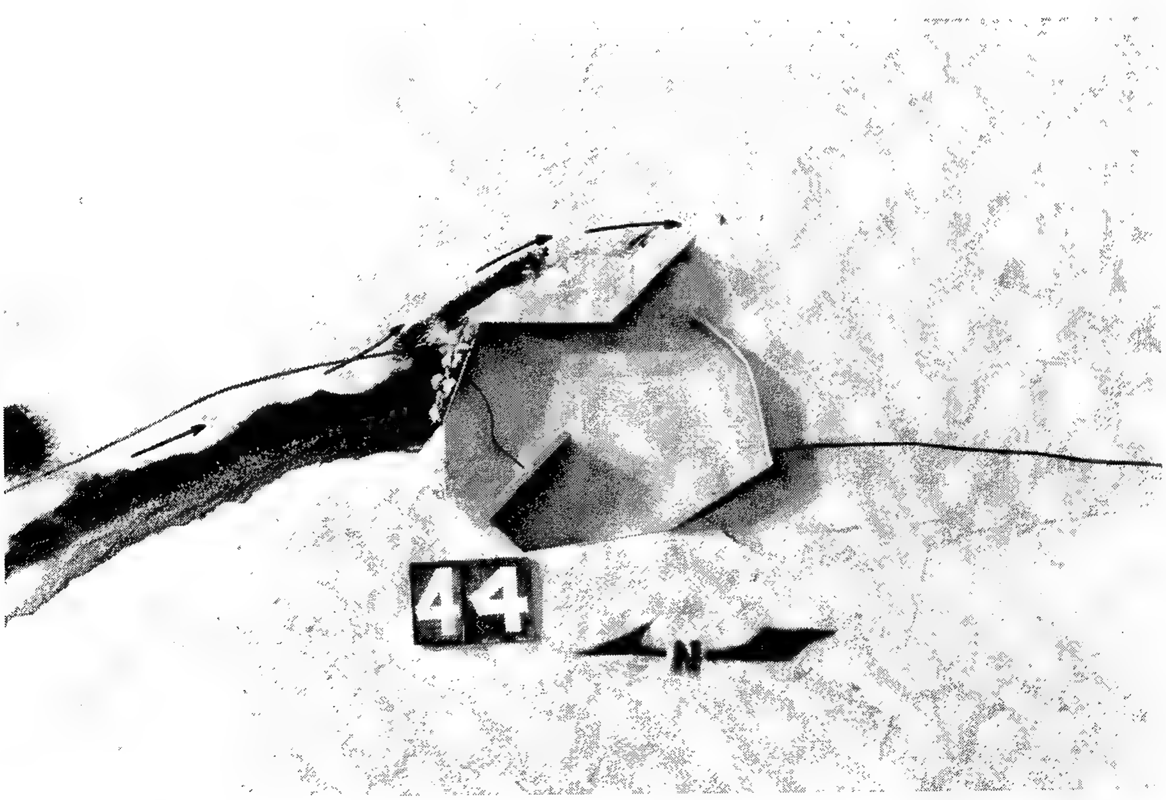



Photo 40. General movement of tracer material and subsequent deposits for Plan 2; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

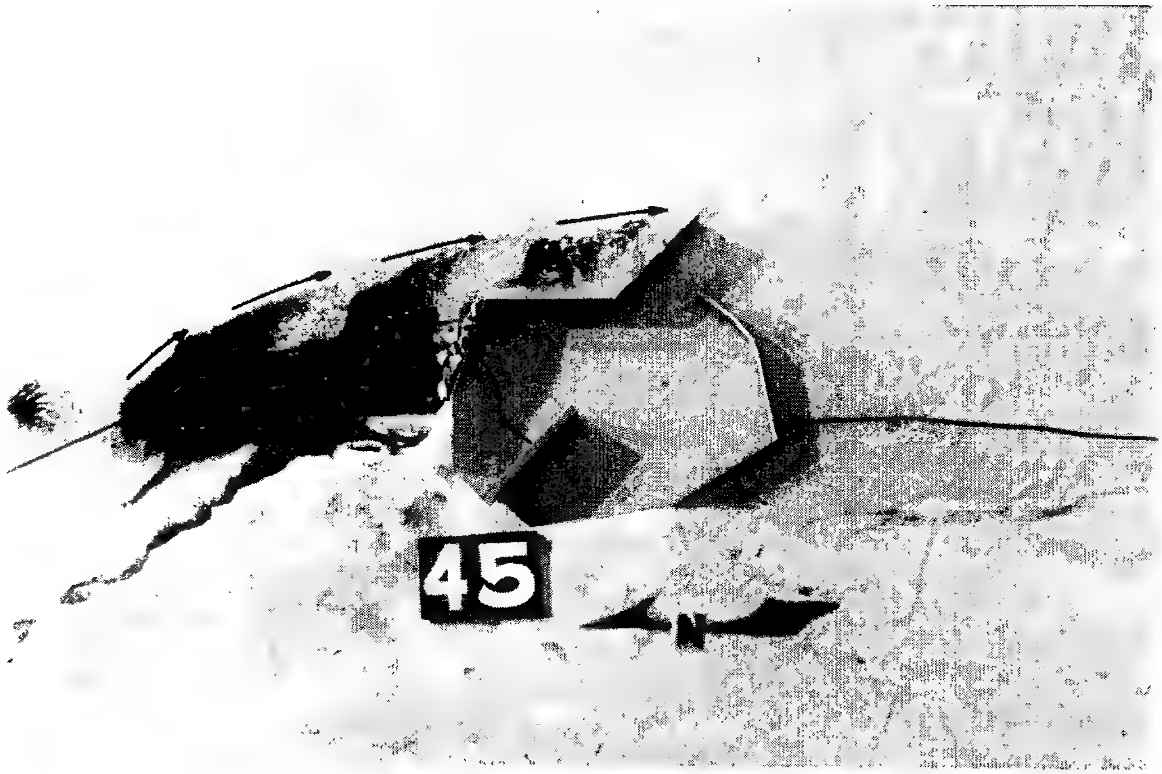



Photo 41. General movement of tracer material and subsequent deposits for Plan 2; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

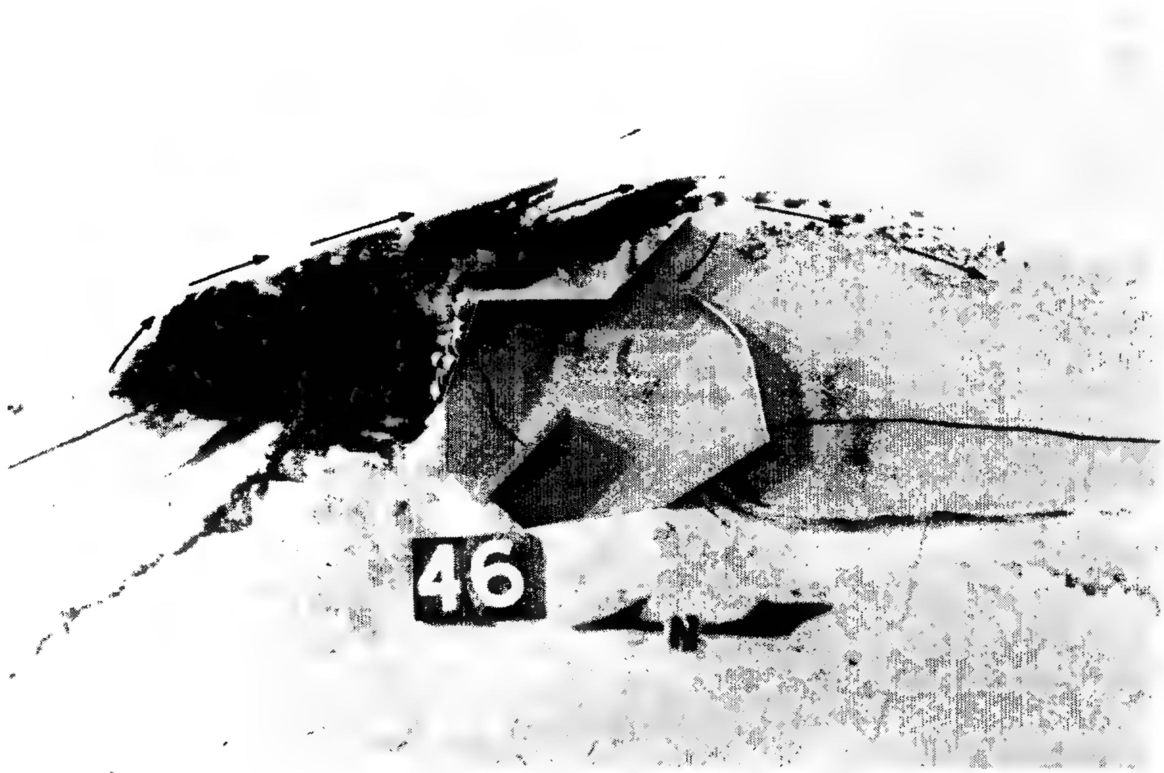



Photo 42. General movement of tracer material and subsequent deposits for Plan 2; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from from 11 deg; swl = +3.5 ft (with riverflow conditions)


Photo 43. General movement of tracer material and subsequent deposits for Plan 3; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

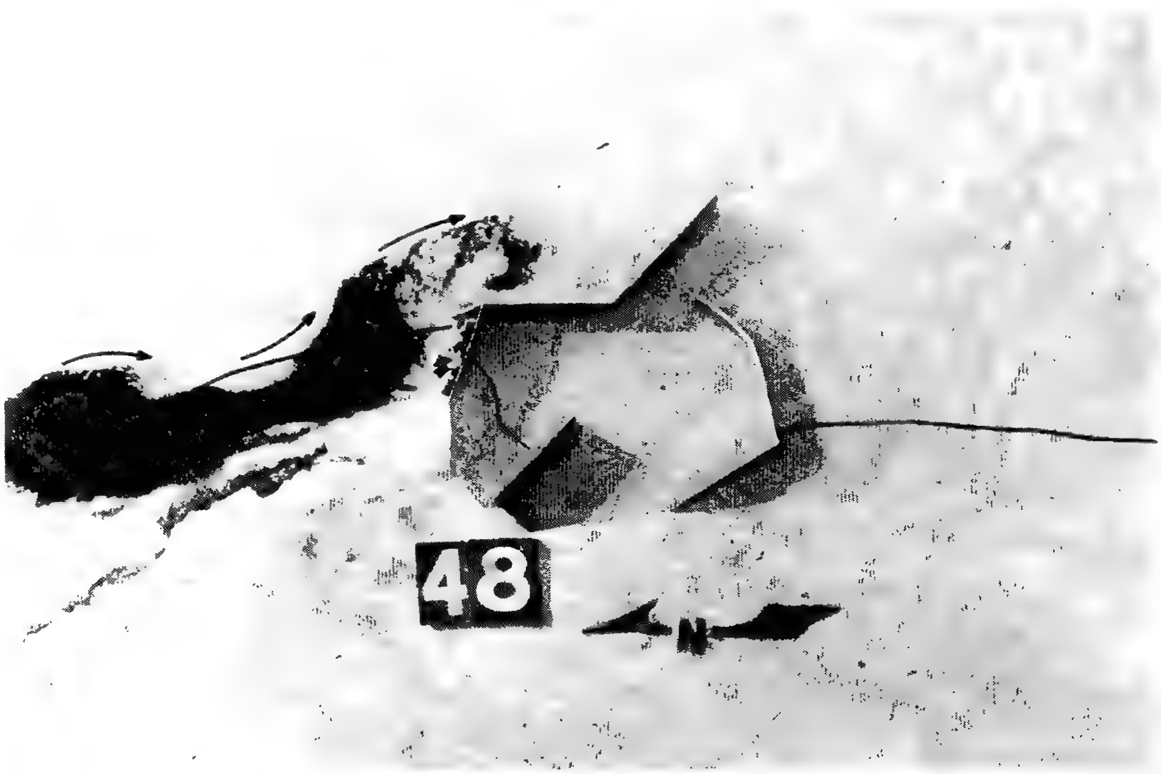



Photo 44. General movement of tracer material and subsequent deposits for Plan 3; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

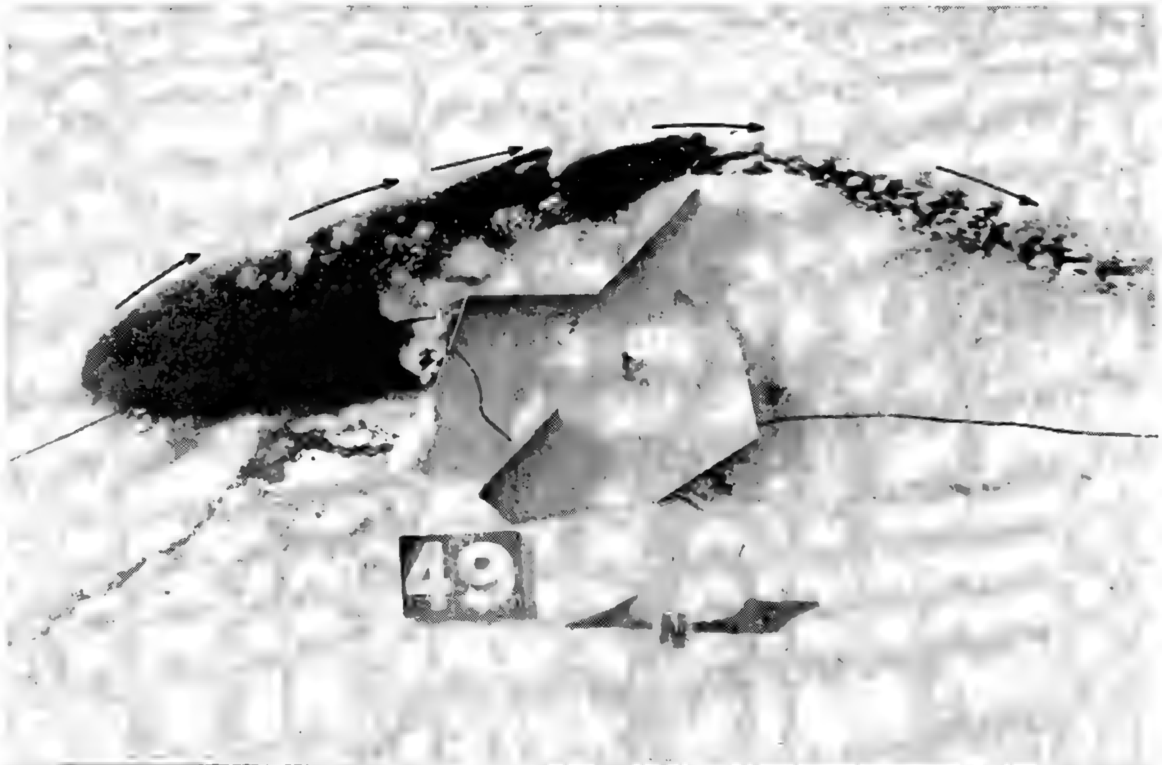



Photo 45. General movement of tracer material and subsequent deposits for Plan 3; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

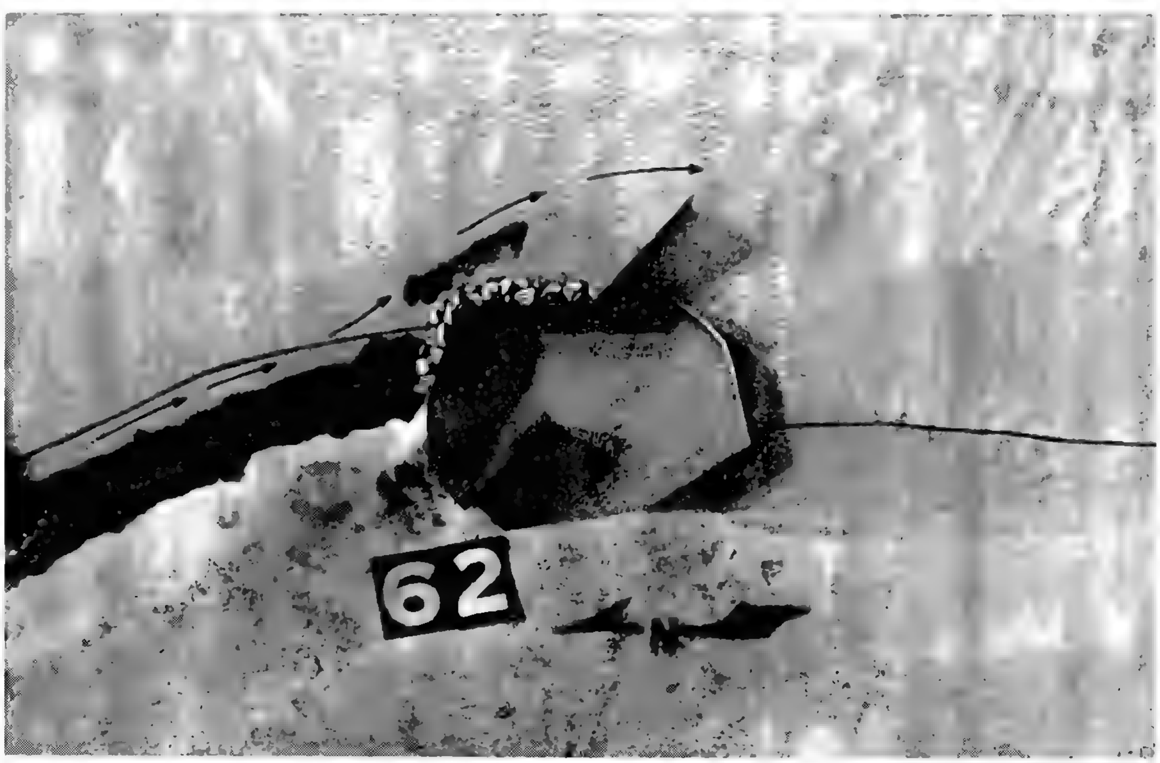



Photo 46. General movement of tracer material and subsequent deposits for Plan 4; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

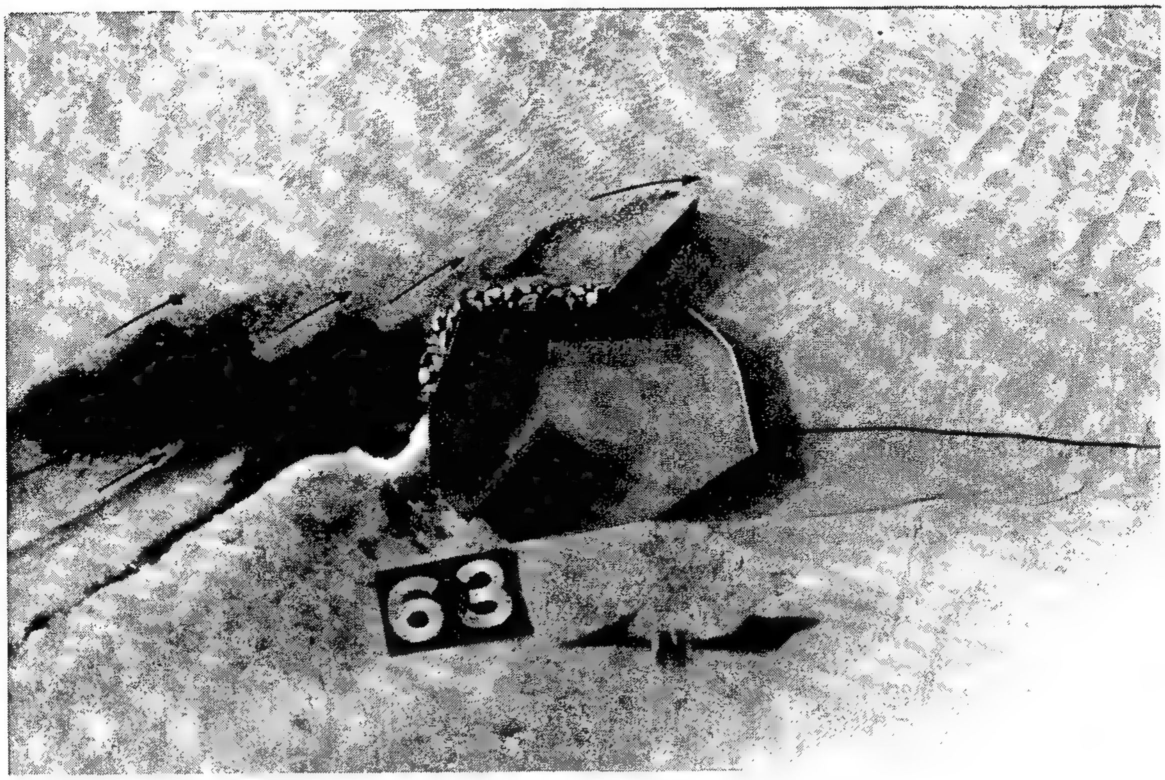



Photo 47. General movement of tracer material and subsequent deposits for Plan 4; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

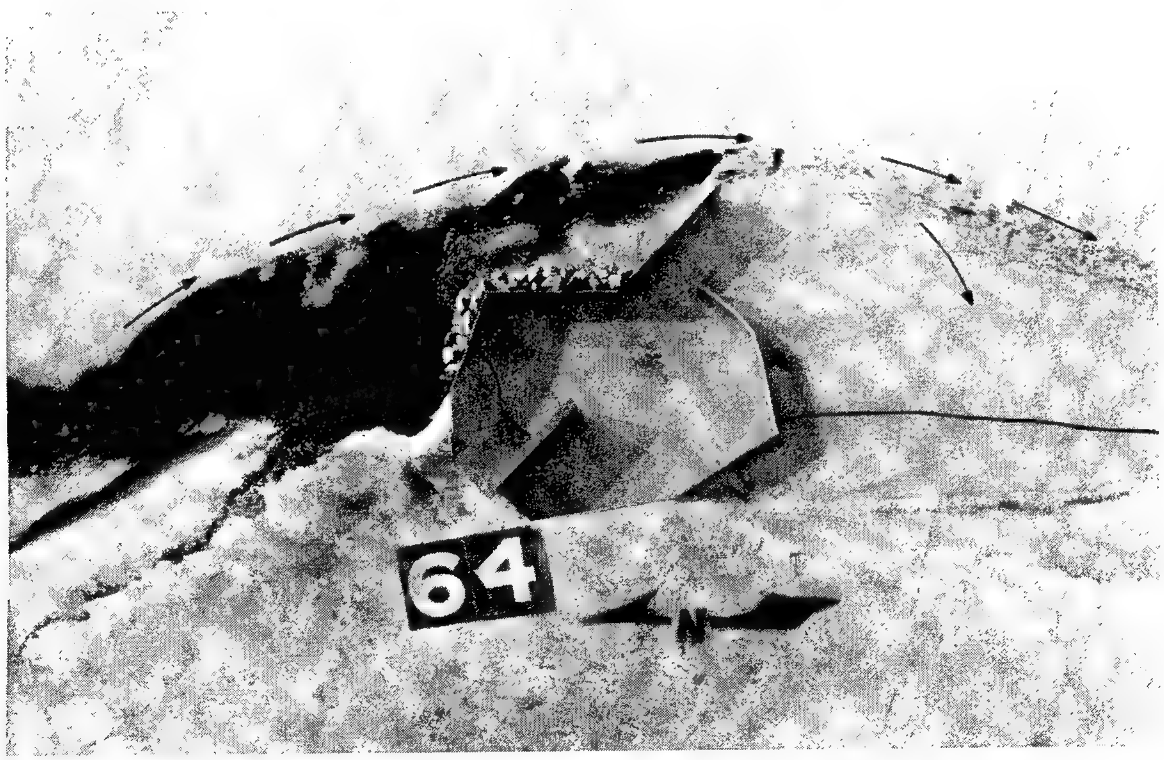



Photo 48. General movement of tracer material and subsequent deposits for Plan 4; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

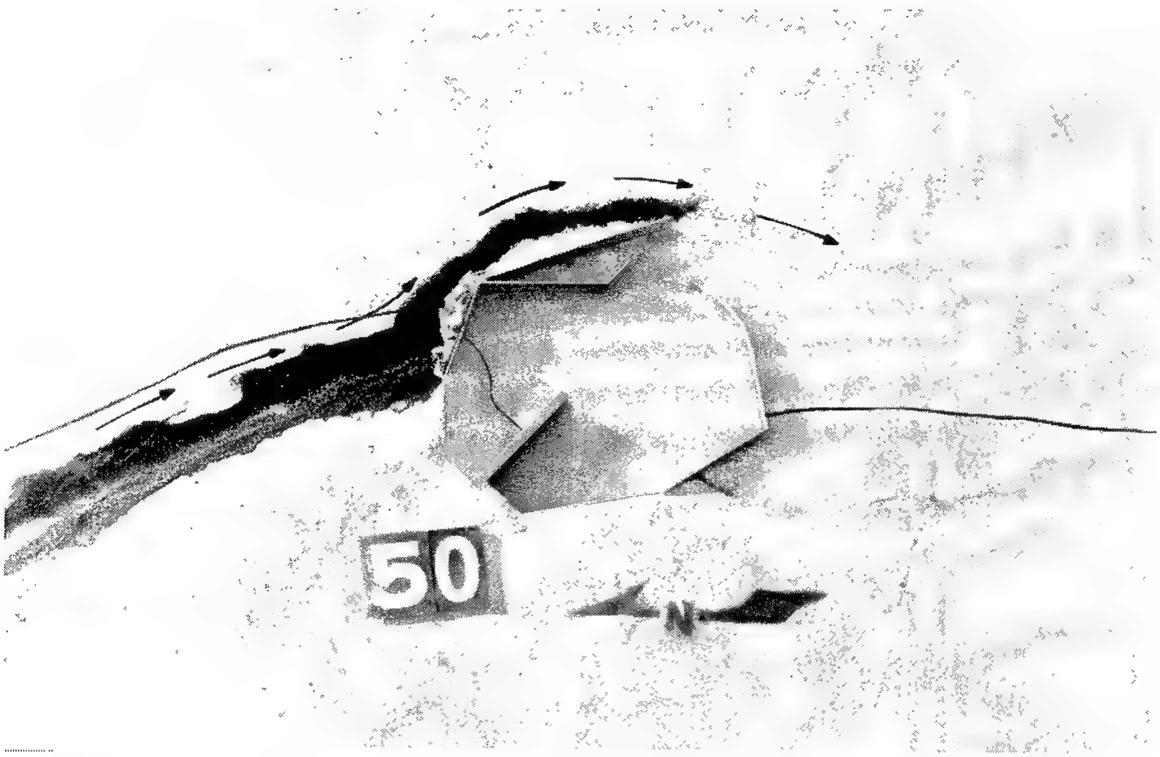



Photo 49. General movement of tracer material and subsequent deposits for Plan 5; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

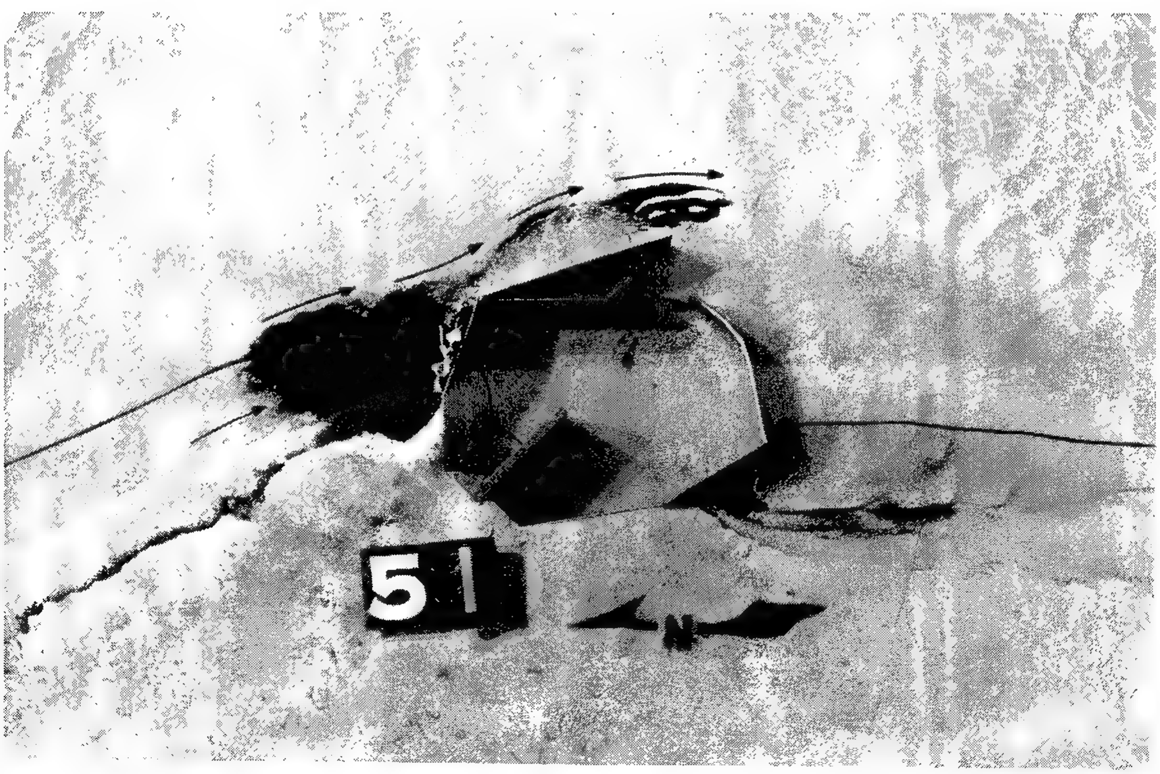



Photo 50. General movement of tracer material and subsequent deposits for Plan 5; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

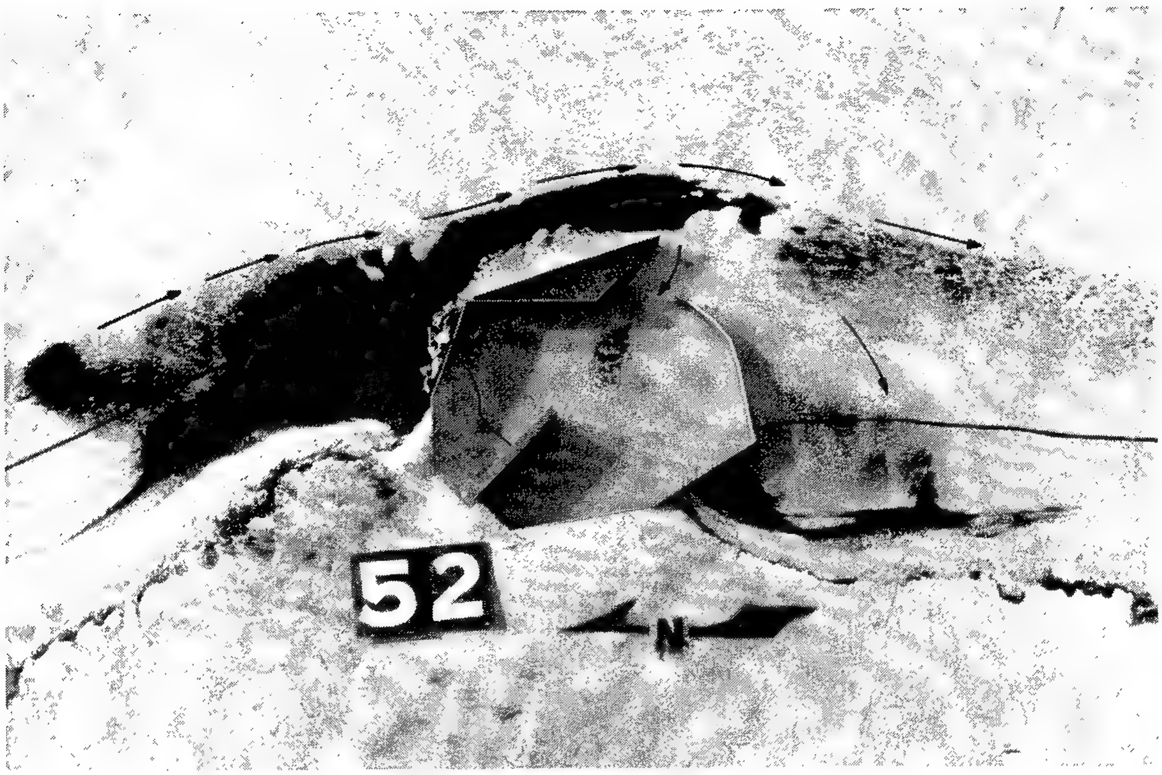



Photo 51. General movement of tracer material and subsequent deposits for Plan 5; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

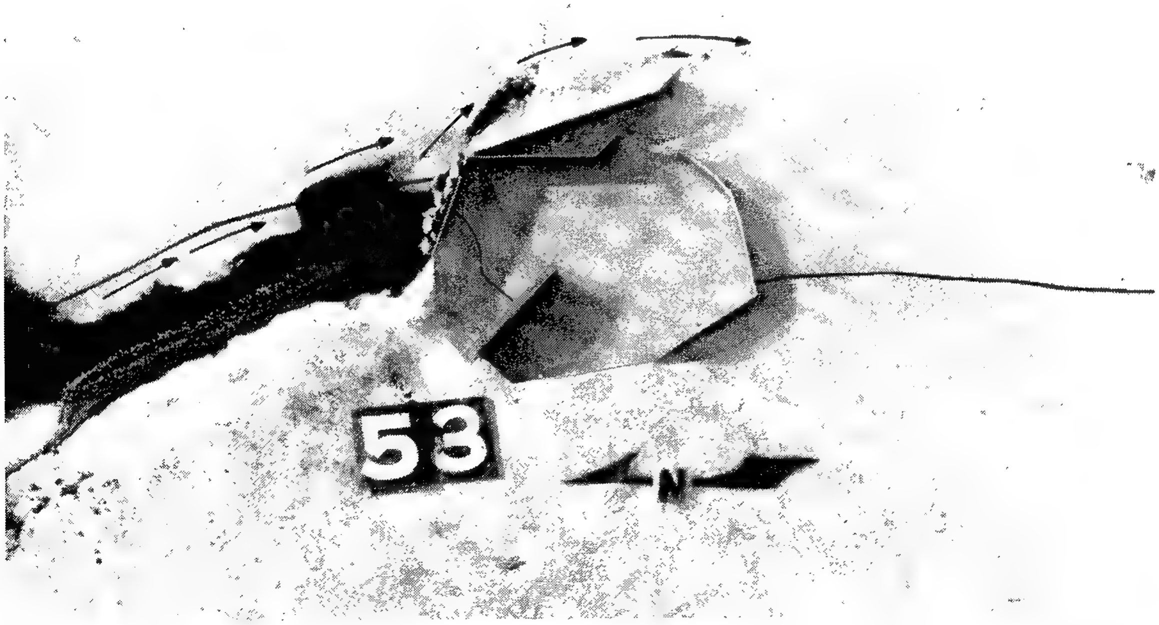



Photo 52. General movement of tracer material and subsequent deposits for Plan 6; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

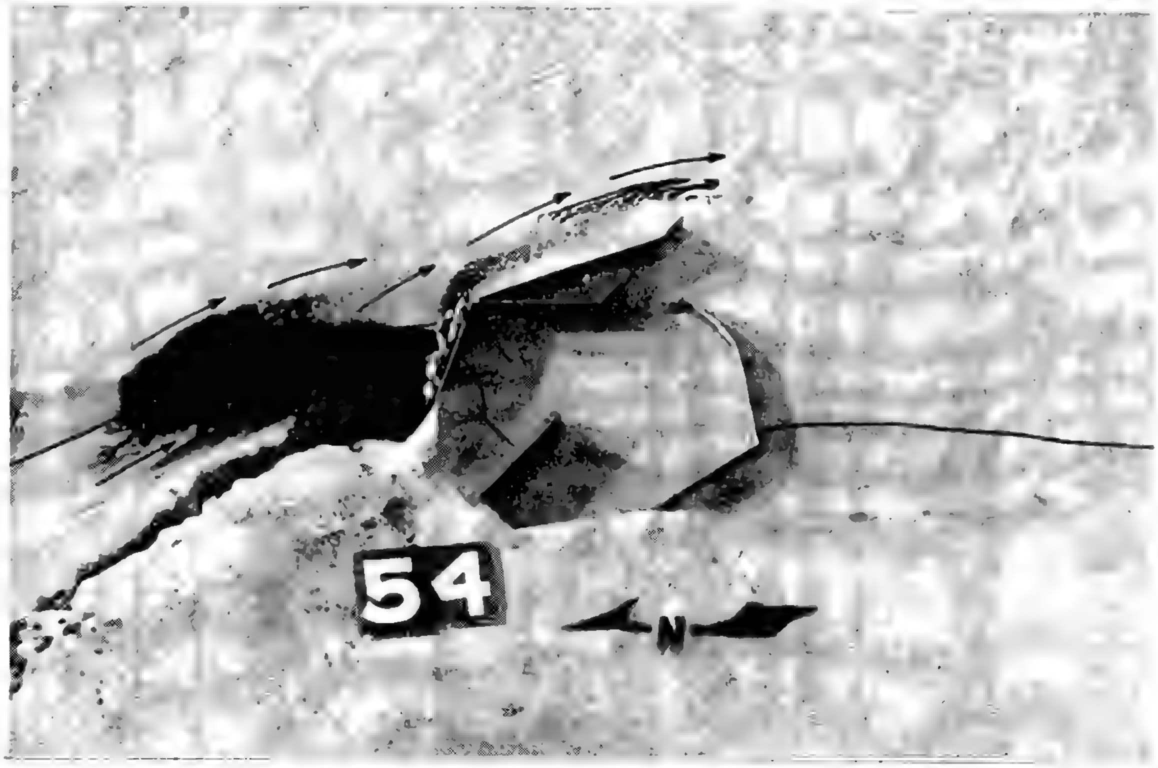



Photo 53. General movement of tracer material and subsequent deposits for Plan 6; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

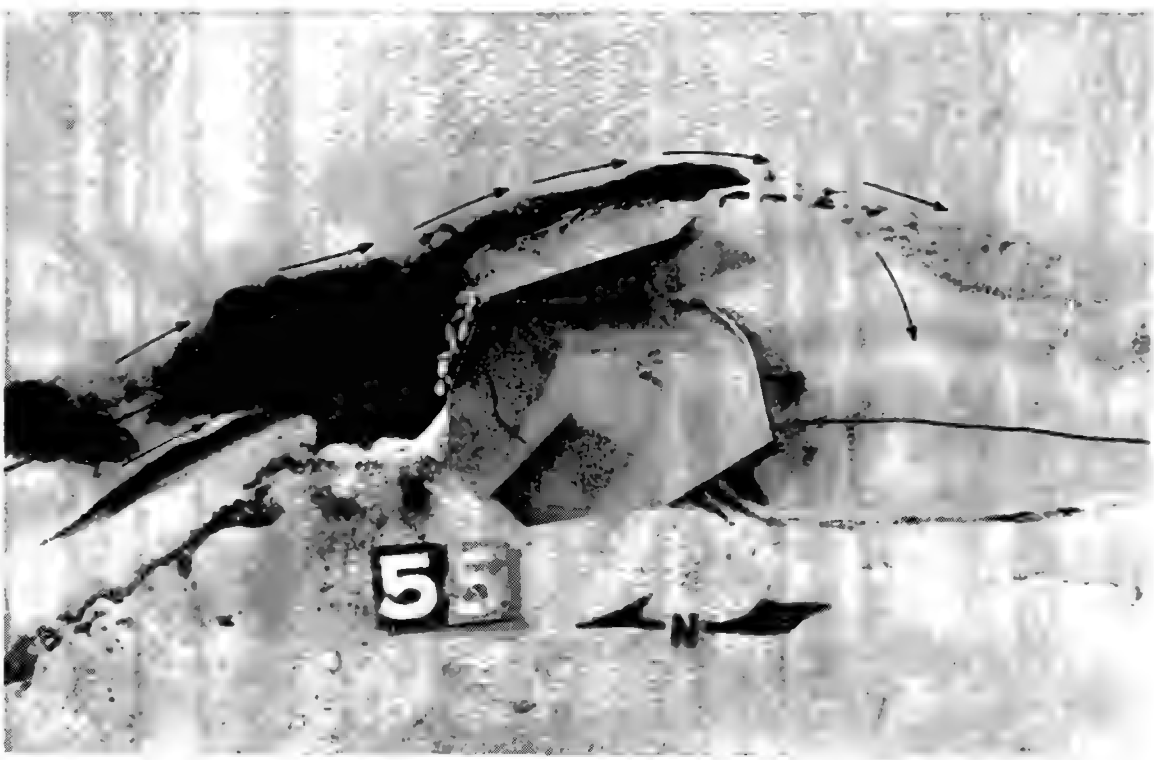



Photo 54. General movement of tracer material and subsequent deposits for Plan 6; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

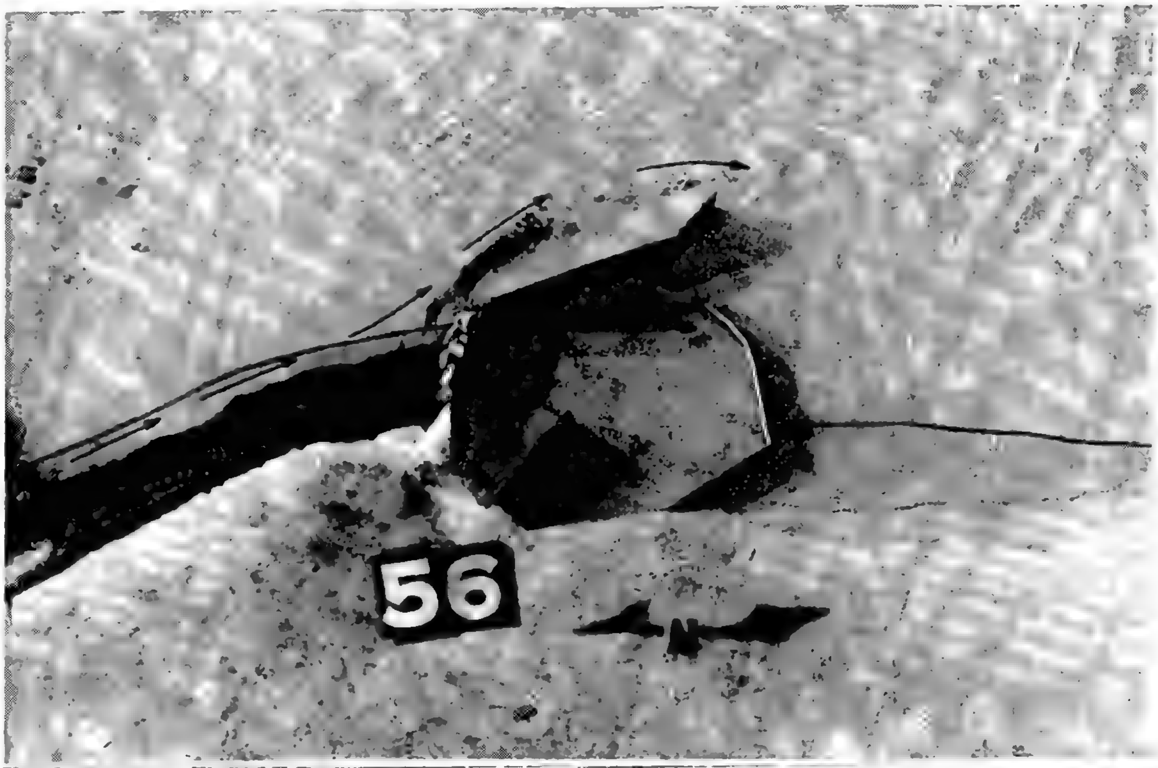



Photo 55. General movement of tracer material and subsequent deposits for Plan 7; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

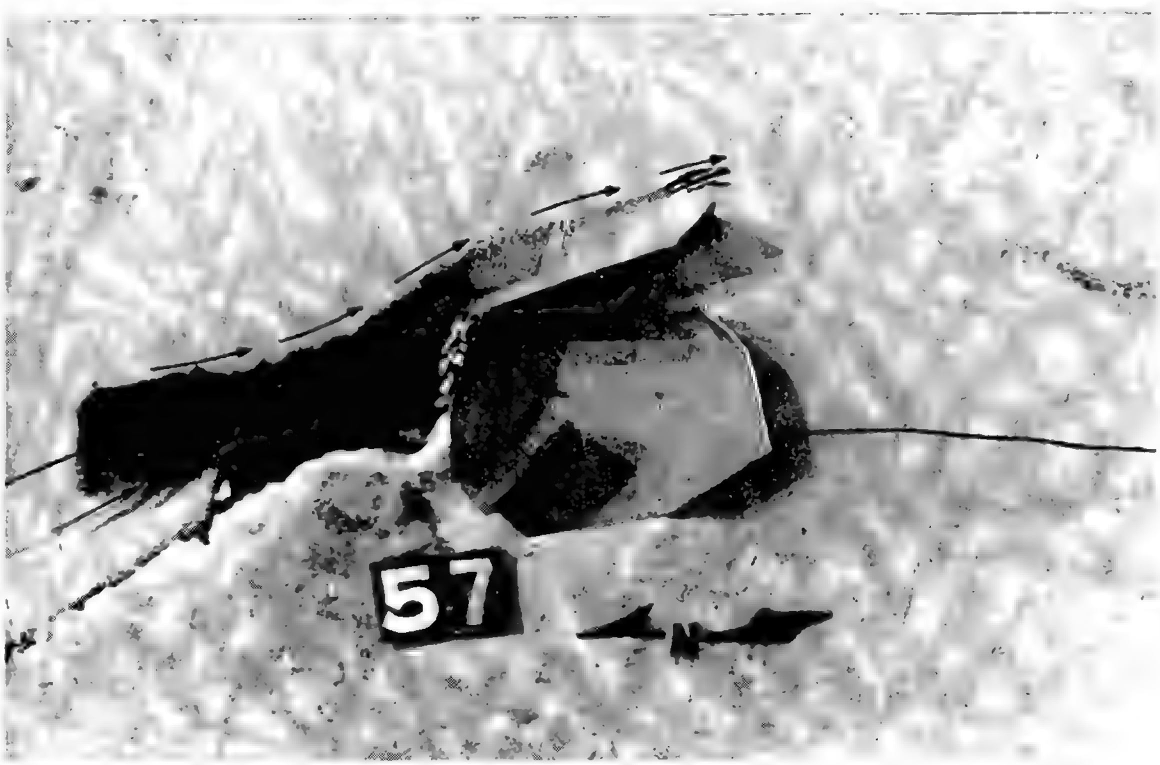



Photo 56. General movement of tracer material and subsequent deposits for Plan 7; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

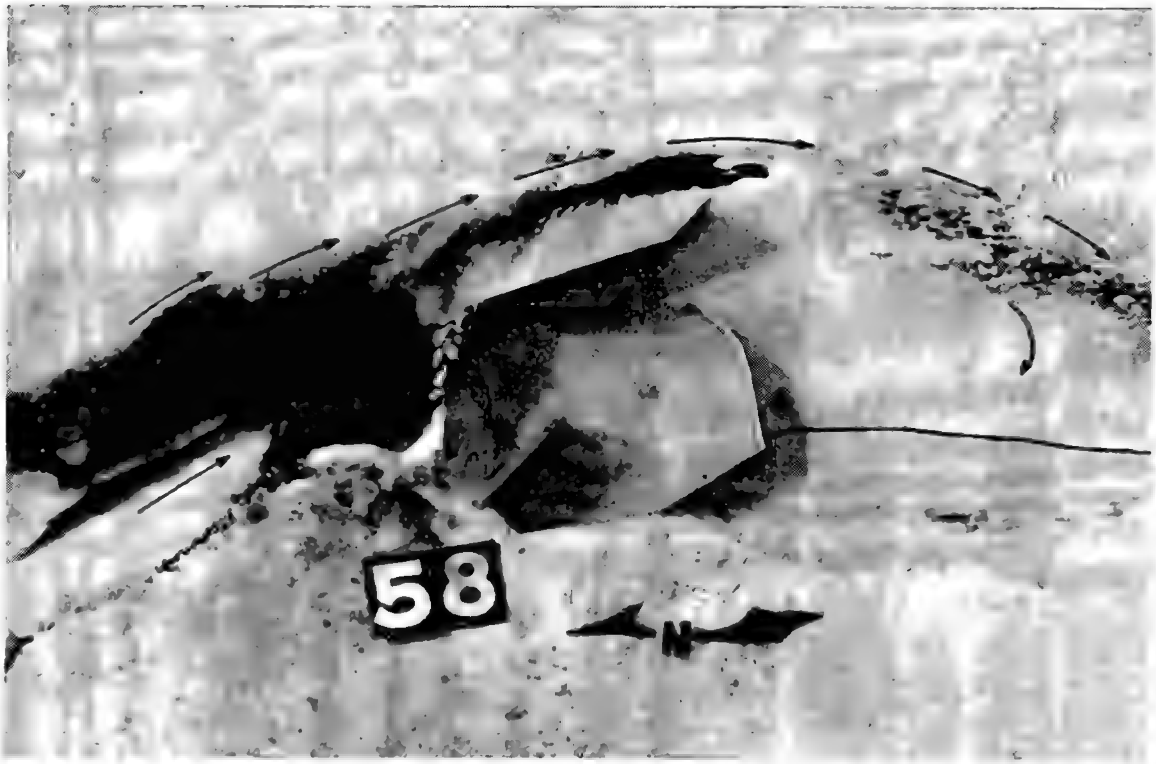



Photo 57. General movement of tracer material and subsequent deposits for Plan 7; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

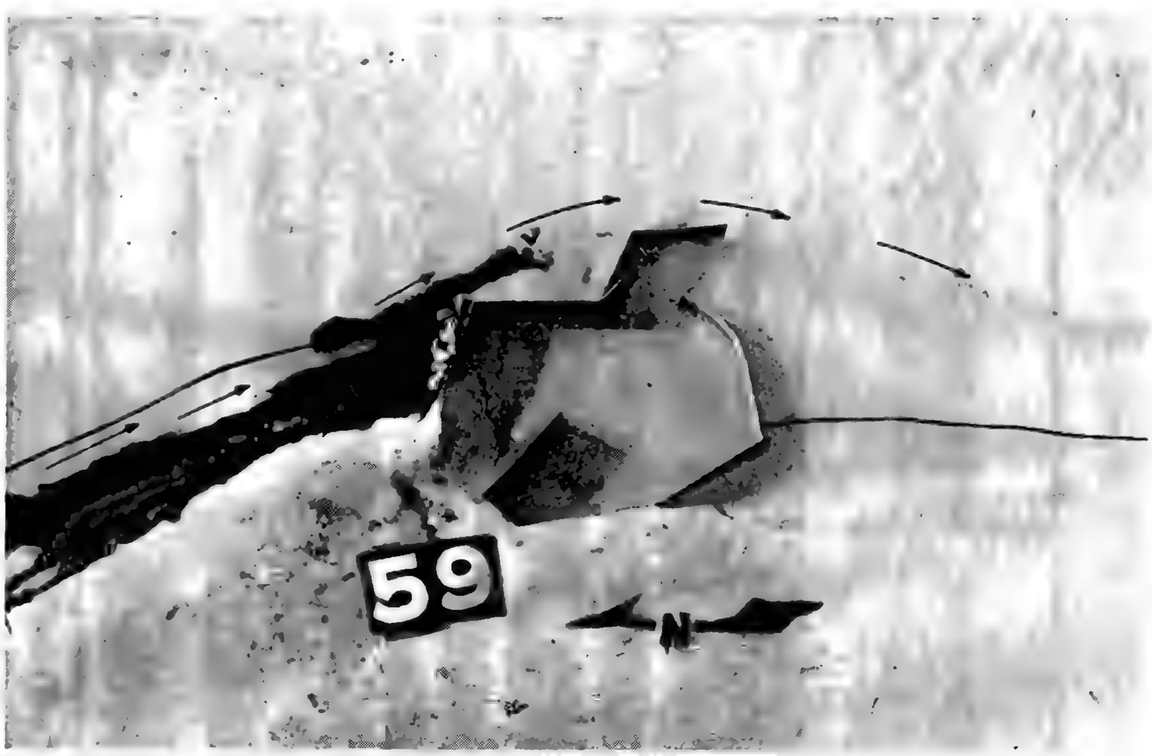



Photo 58. General movement of tracer material and subsequent deposits for Plan 8; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

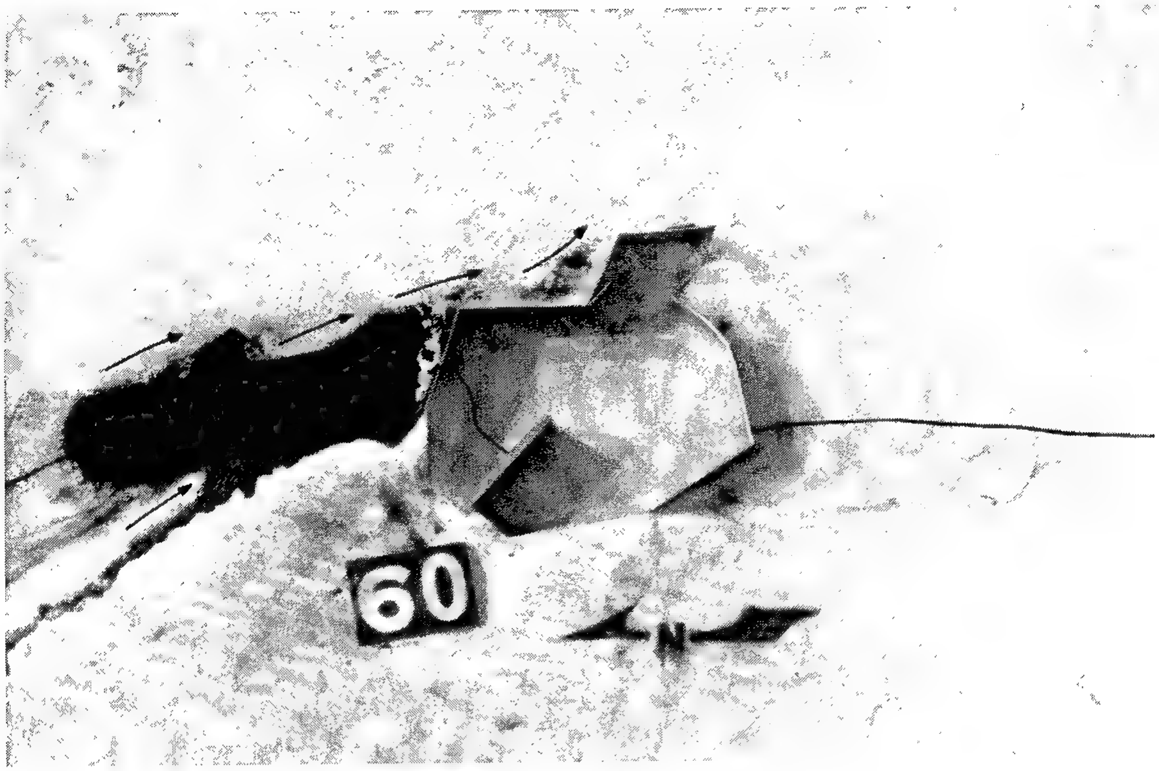



Photo 59. General movement of tracer material and subsequent deposits for Plan 8; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

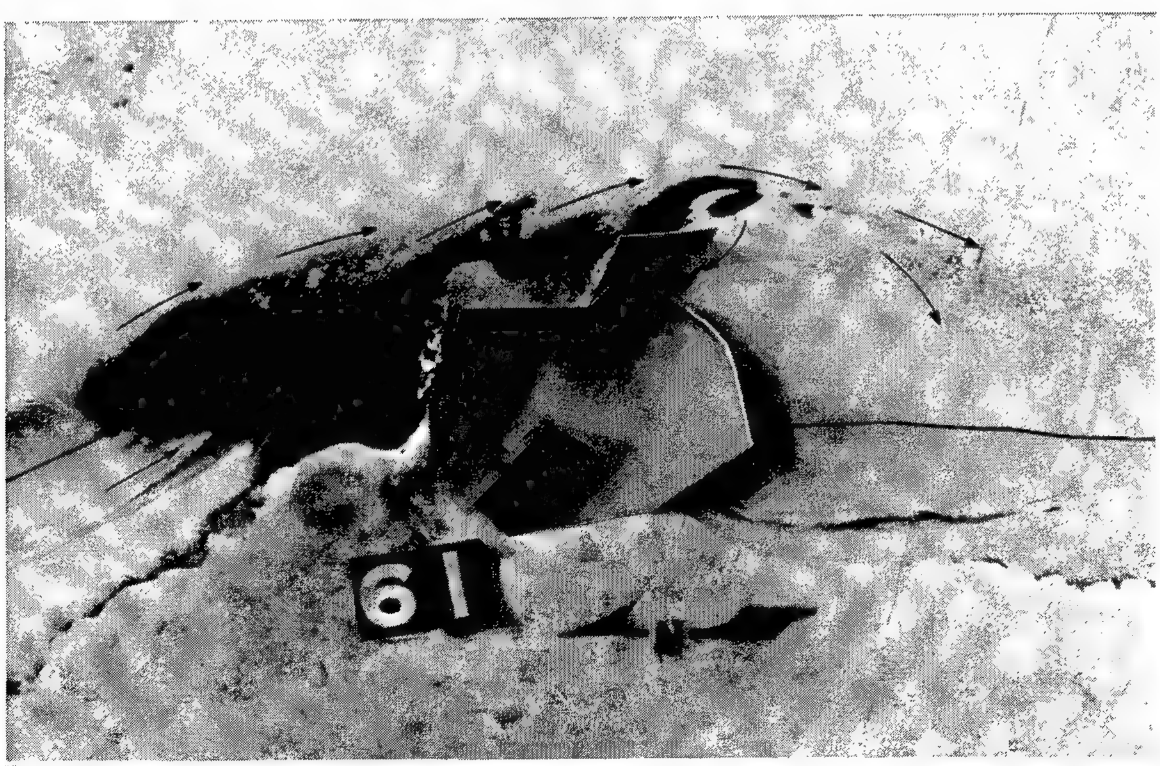



Photo 60. General movement of tracer material and subsequent deposits for Plan 8; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

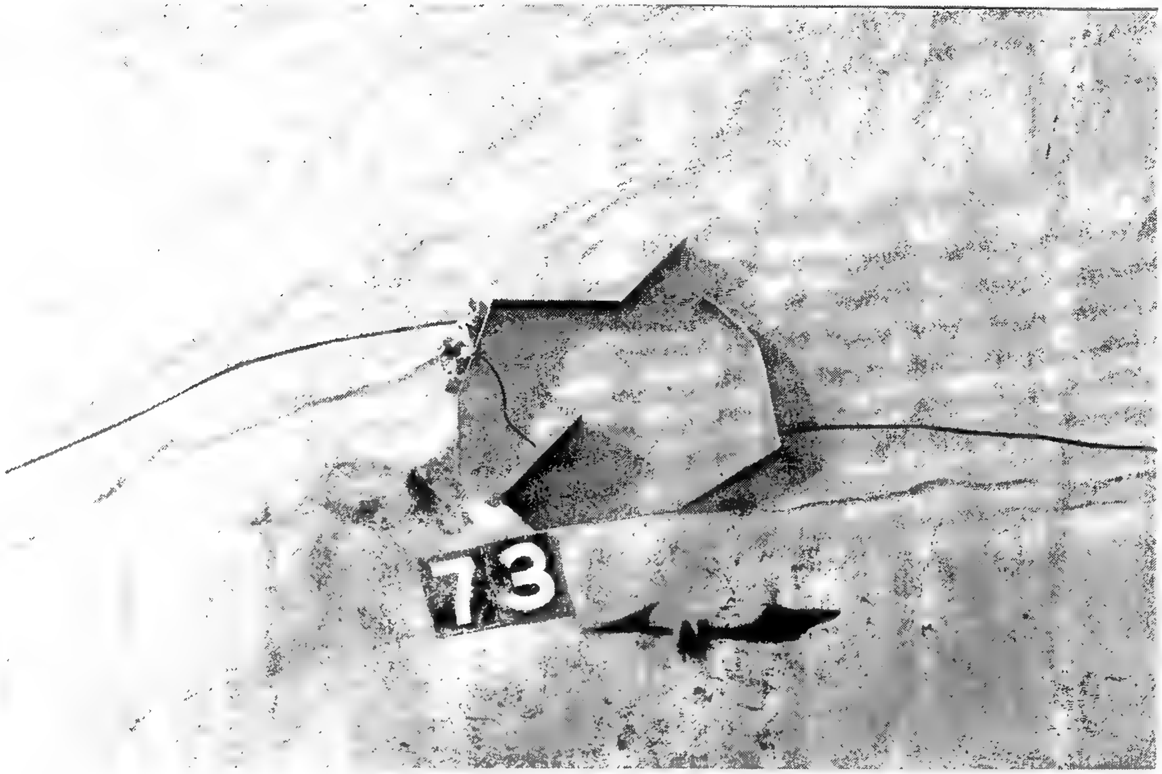



Photo 61. Typical wave patterns for Plan 1; 6.0-sec, 4.0-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

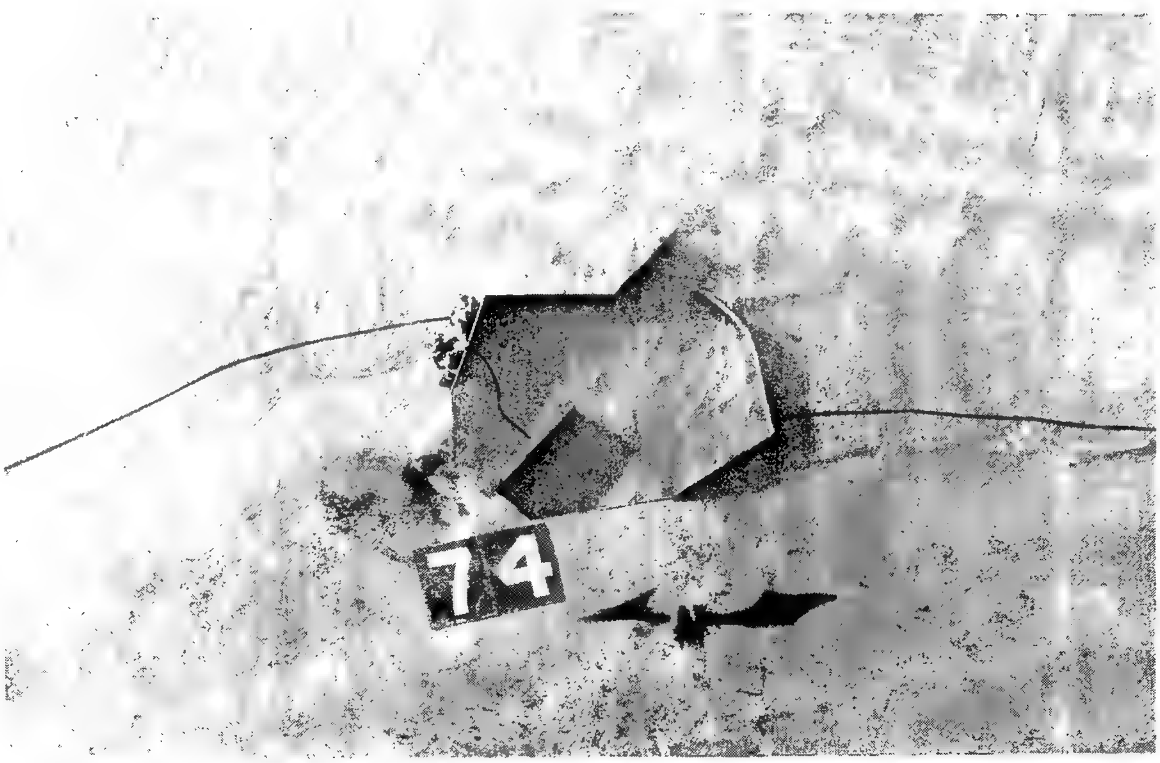



Photo 62. Typical wave patterns for Plan 1; 8.6-sec, 8.6-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

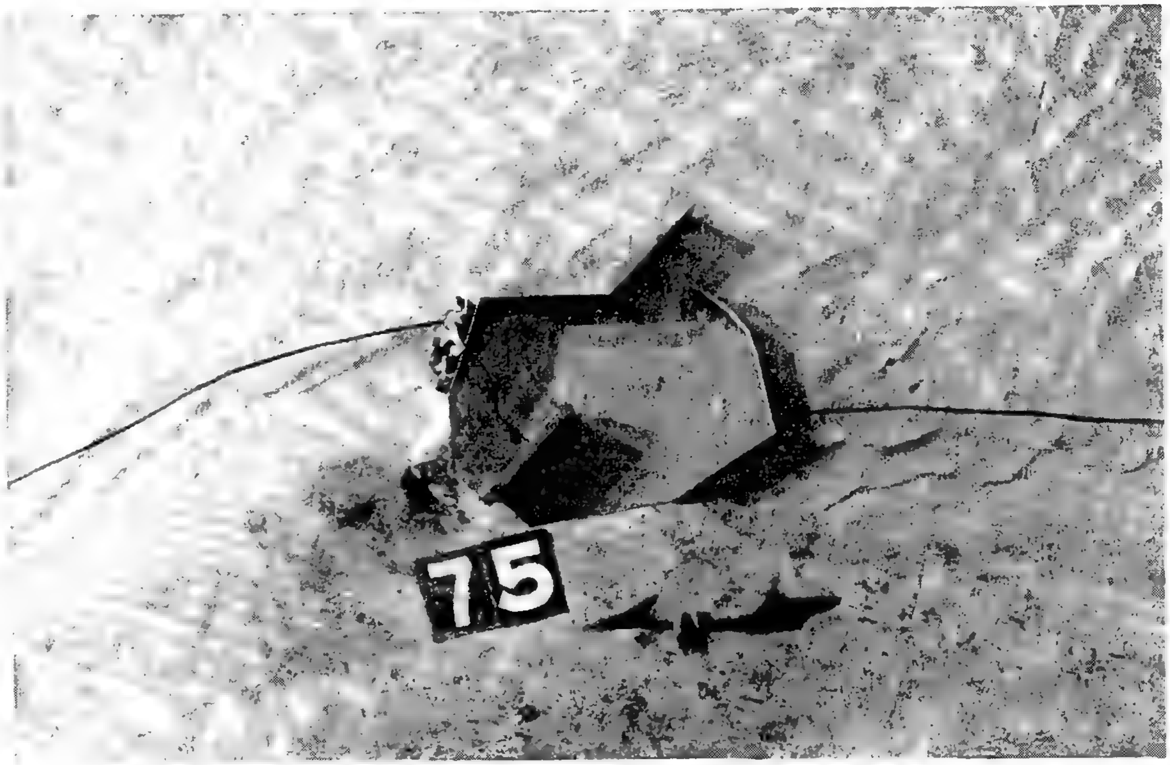



Photo 63. Typical wave patterns for Plan 2; 6.0-sec, 4.0-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

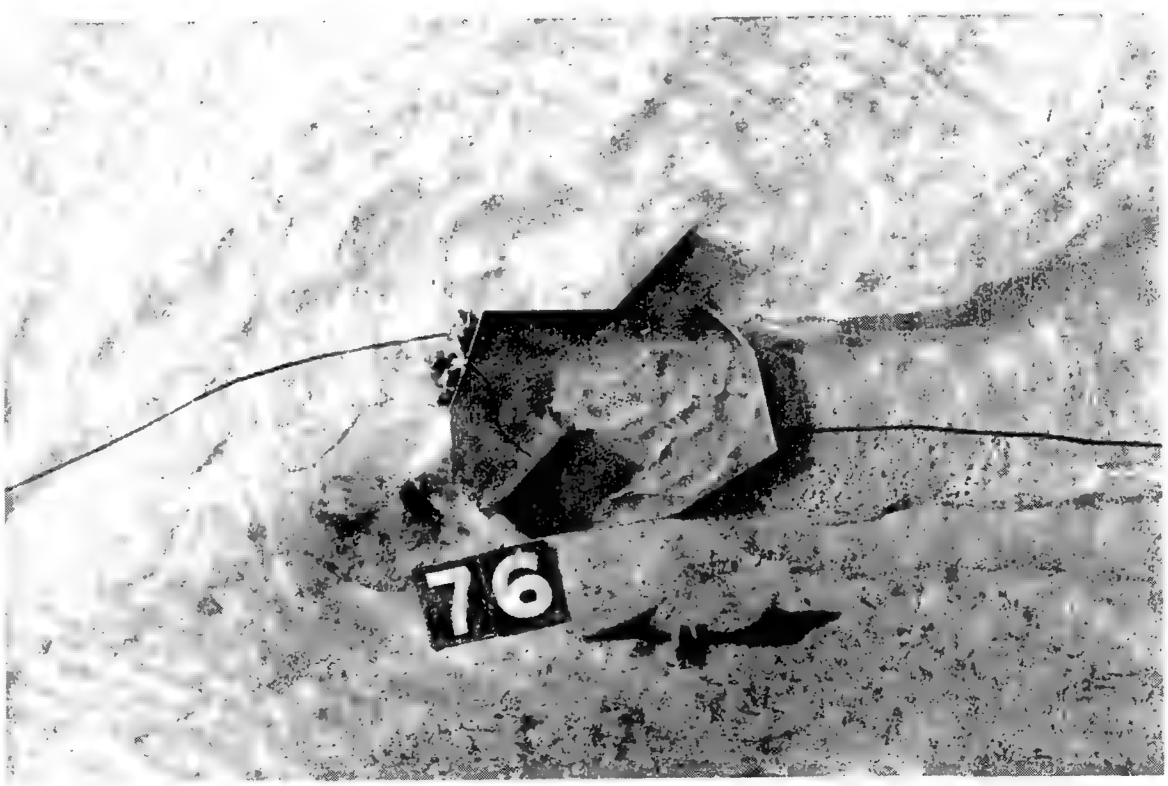



Photo 64. Typical wave patterns for Plan 2; 8.6-sec, 8.6-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

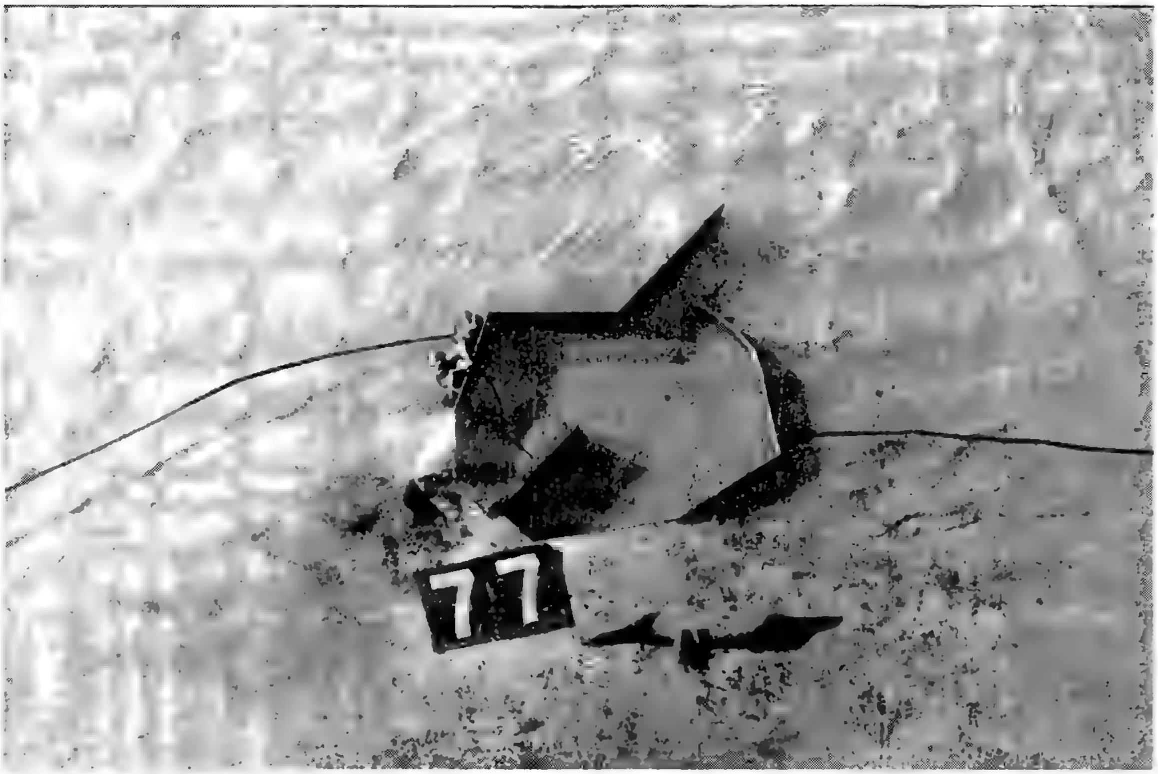



Photo 65. Typical wave patterns for Plan 3; 6.0-sec, 4.0-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

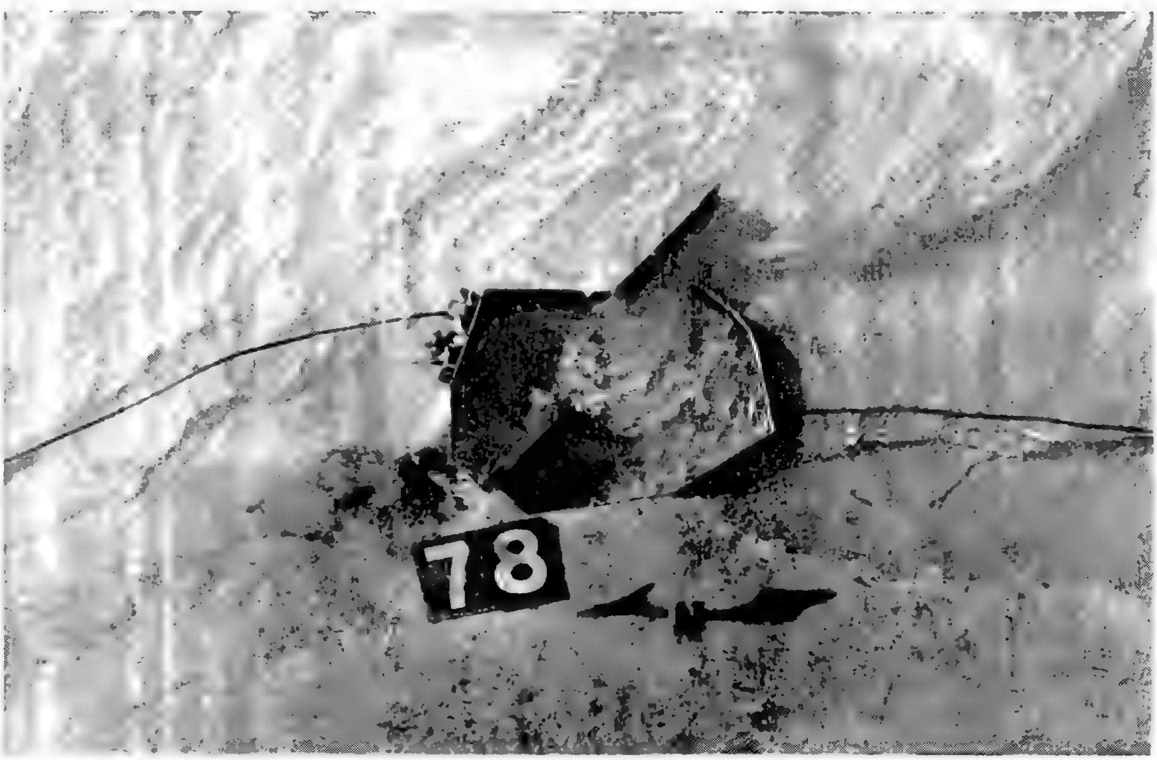



Photo 66. Typical wave patterns for Plan 3; 8.6-sec, 8.6-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

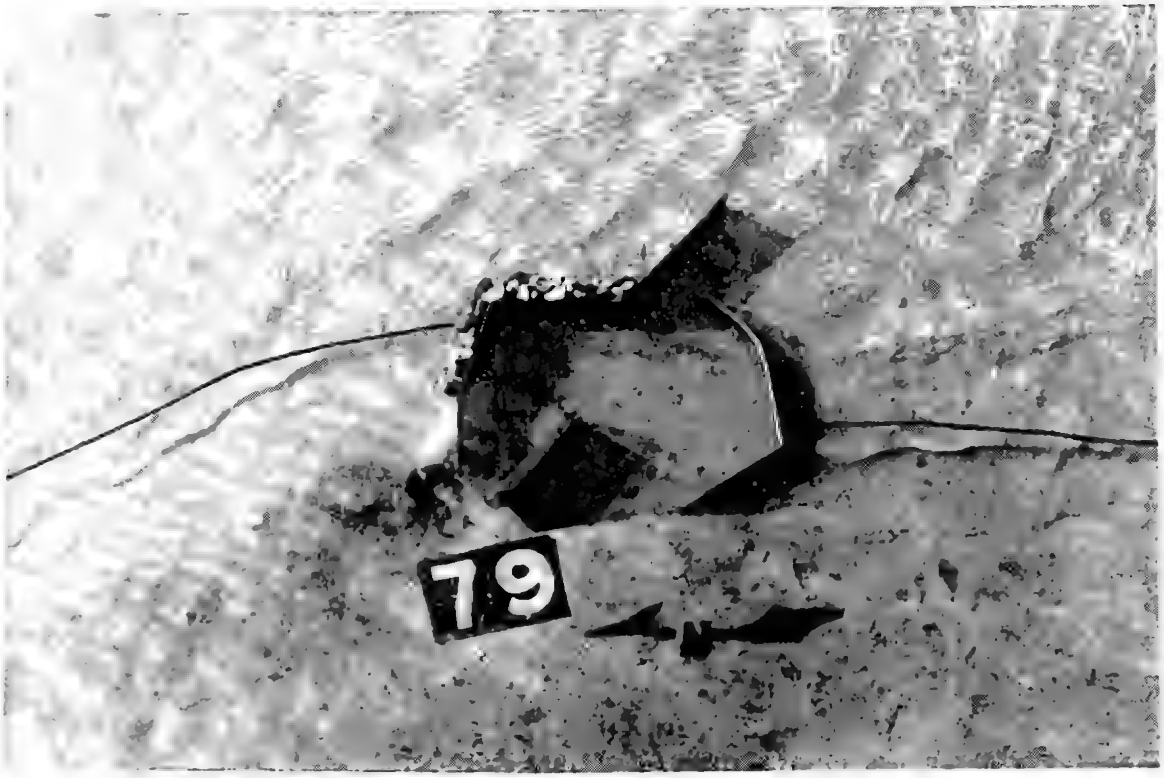



Photo 67. Typical wave patterns for Plan 4; 6.0-sec, 4.0-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

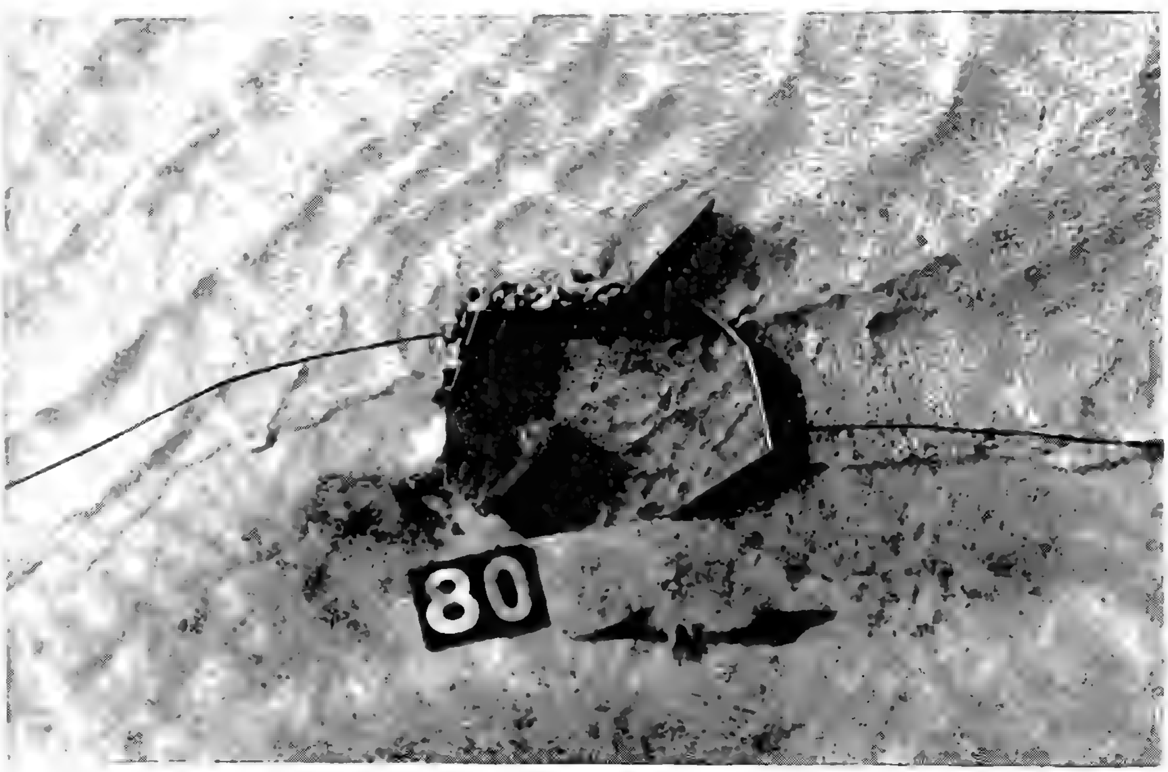



Photo 68. Typical wave patterns for Plan 4; 8.6-sec, 8.6-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

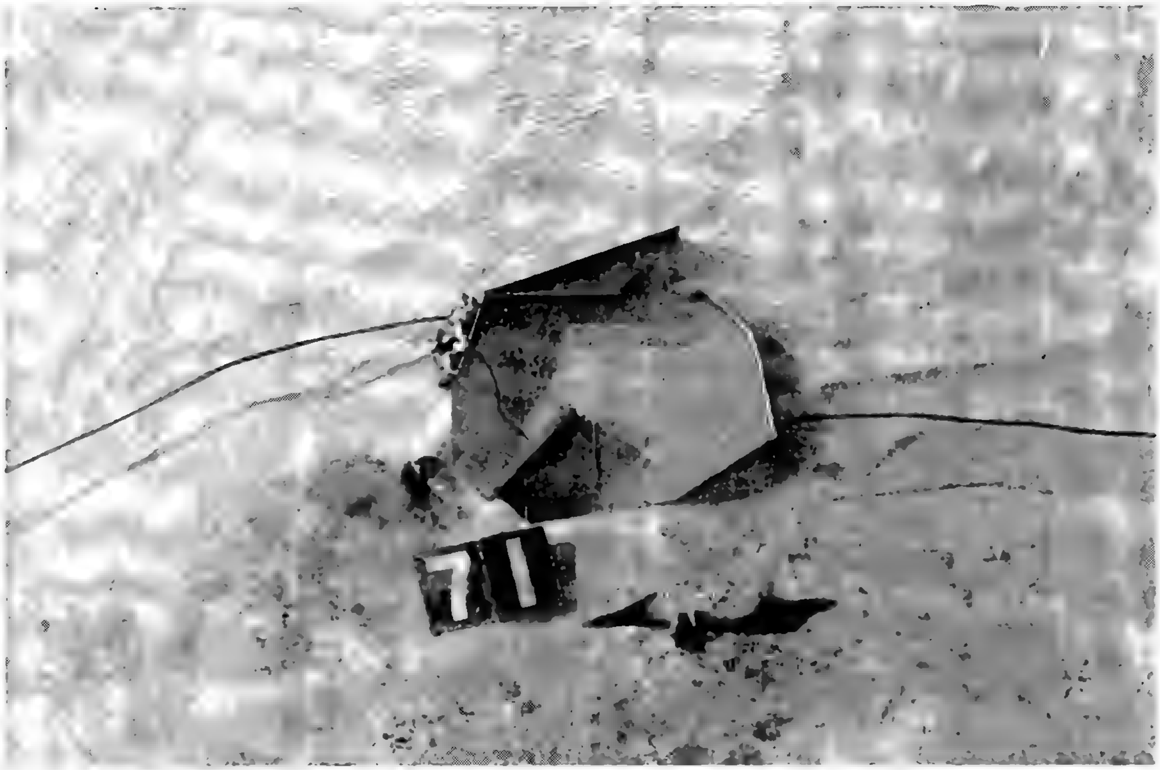



Photo 69. Typical wave patterns for Plan 5; 6.0-sec, 4.0-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)


Photo 70. Typical wave patterns for Plan 5; 8.6-sec, 8.6-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

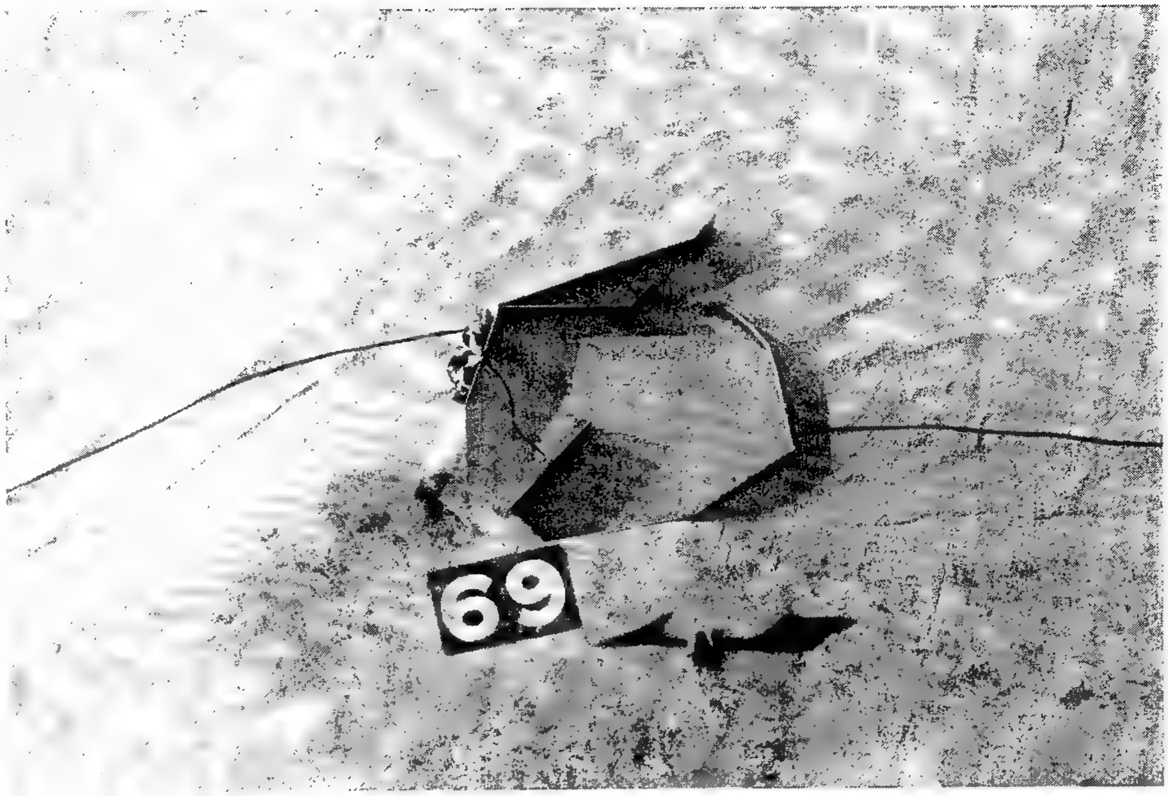



Photo 71. Typical wave patterns for Plan 6; 6.0-sec, 4.0-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

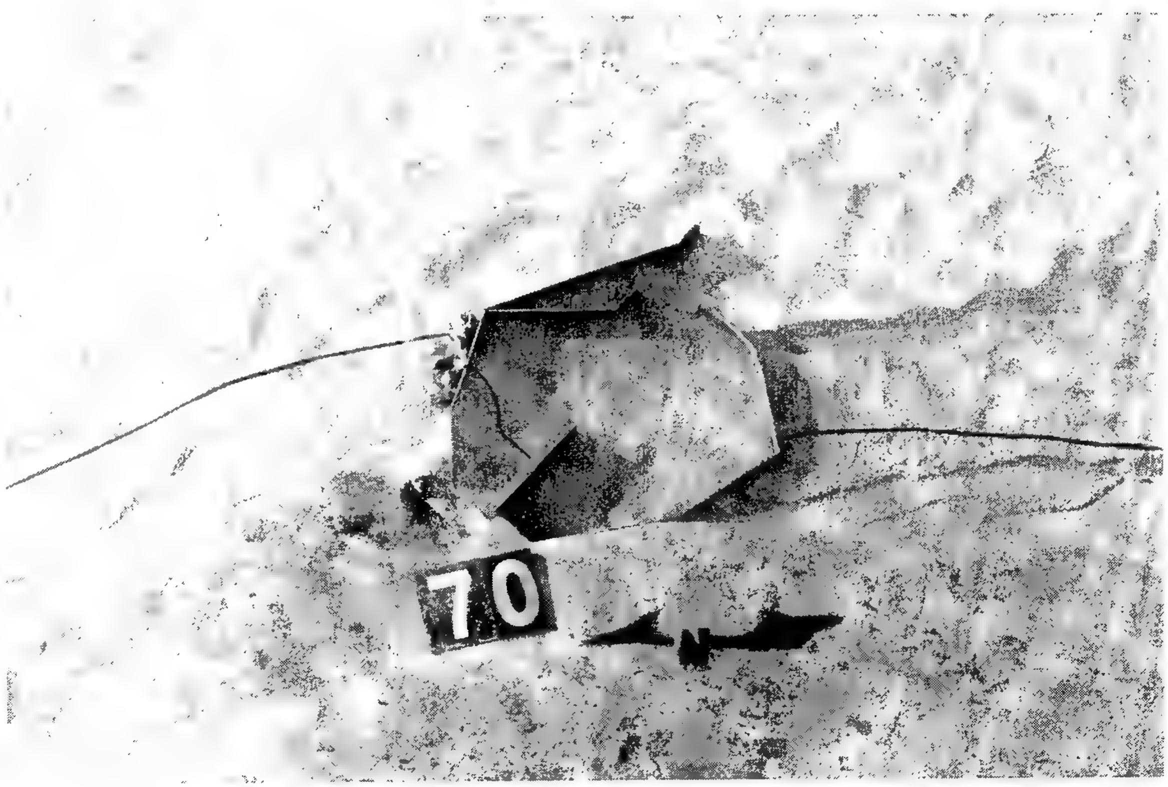



Photo 72. Typical wave patterns for Plan 6; 8.6-sec, 8.6-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

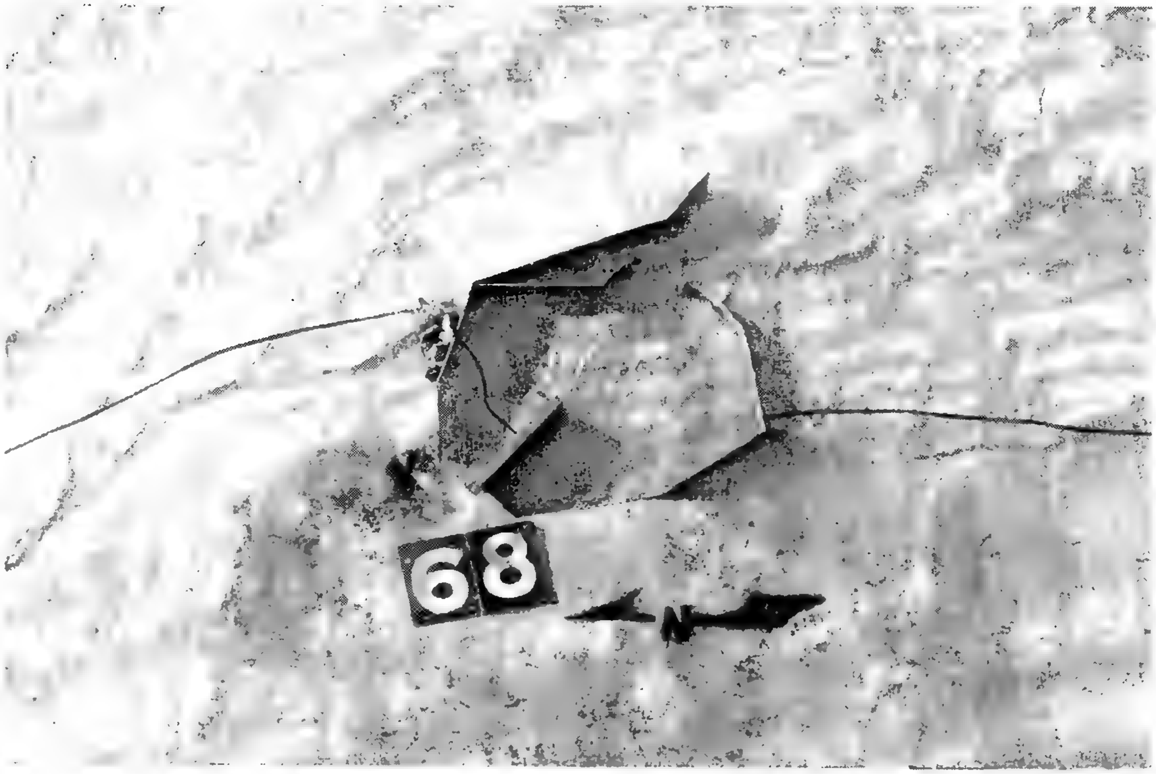



Photo 73. Typical wave patterns for Plan 7; 6.0-sec, 4.0 waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

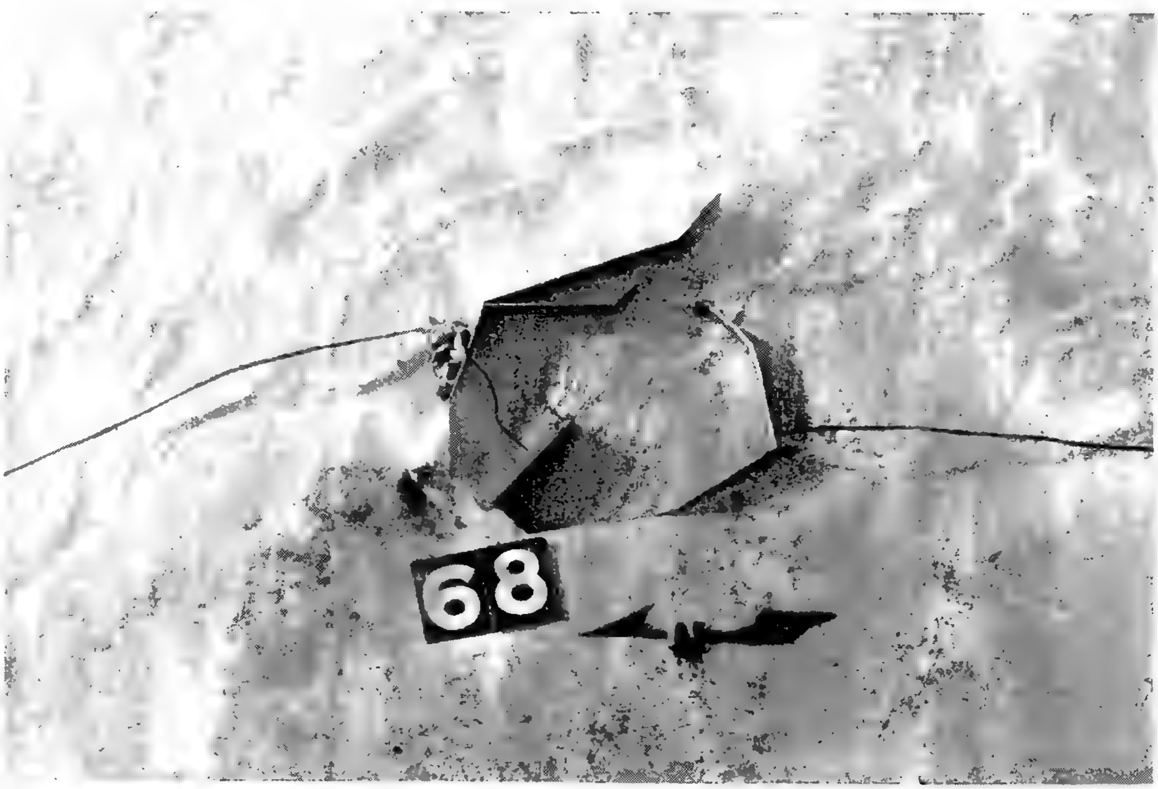



Photo 74. Typical wave patterns for Plan 7; 8.6-sec, 8.6-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

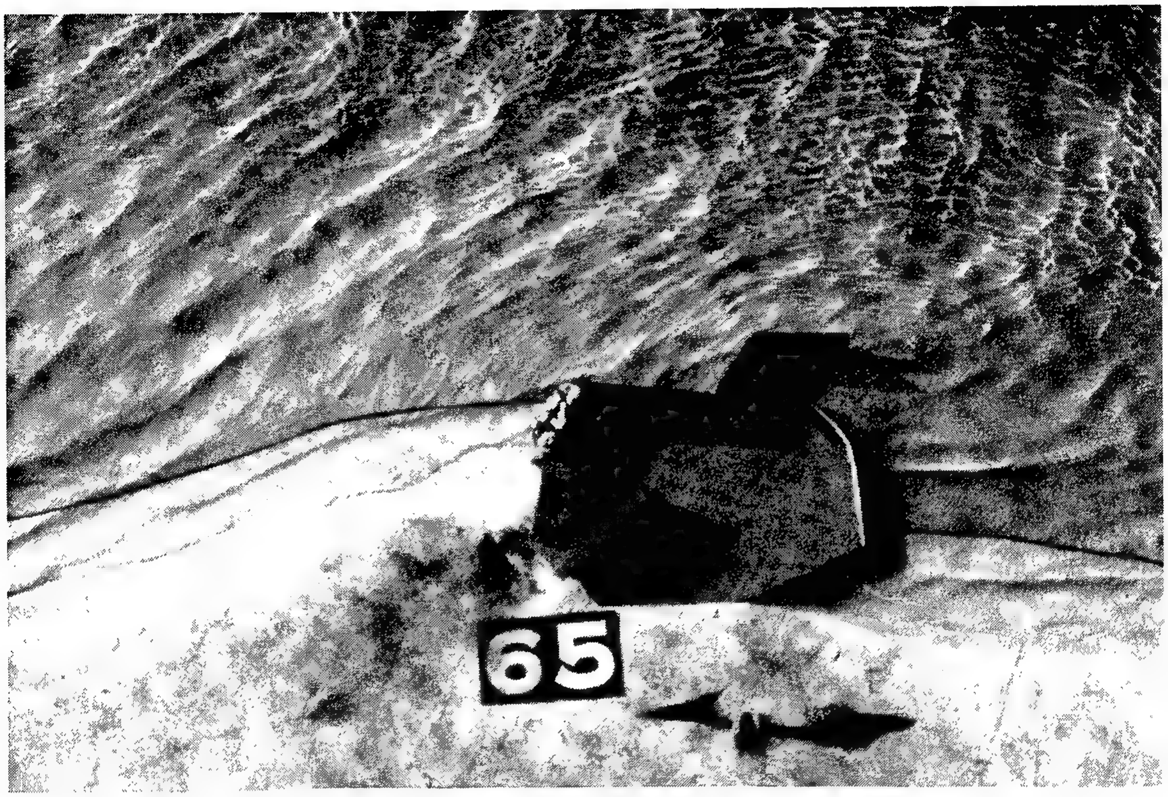



Photo 75. Typical wave patterns for Plan 8; 6.0-sec, 4.0-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

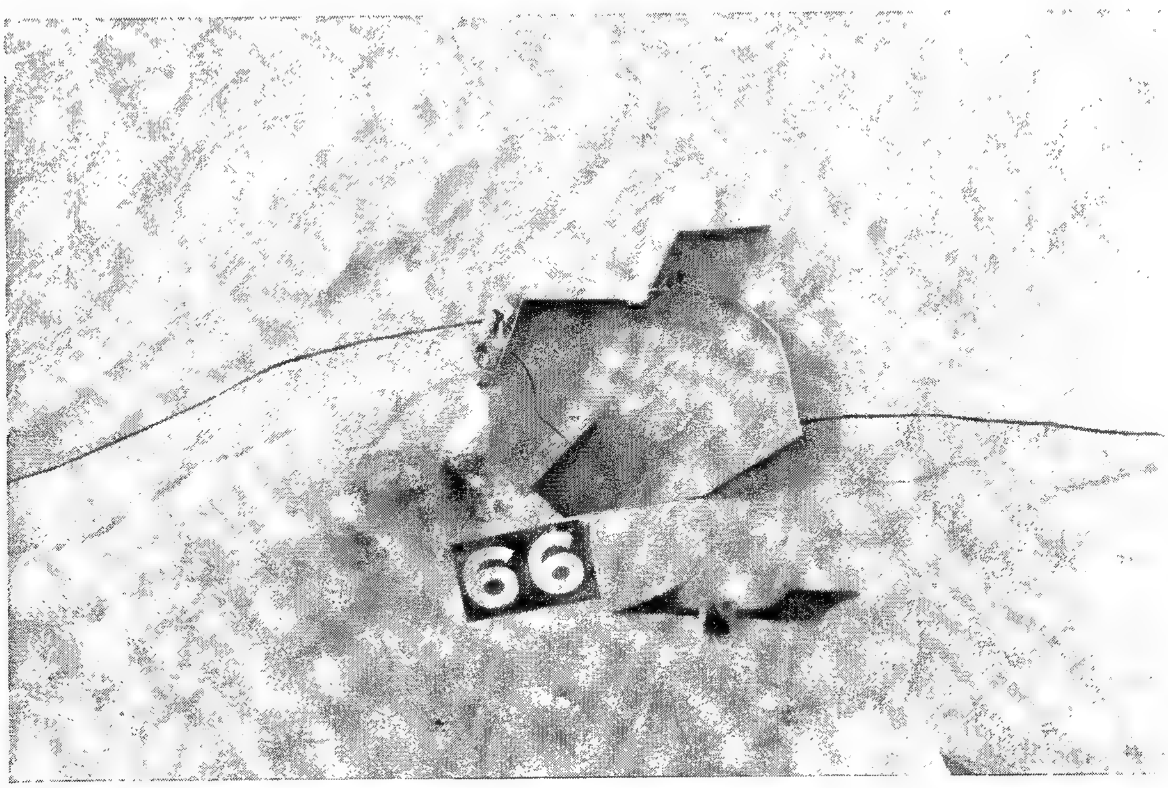



Photo 76. Typical wave patterns for Plan 8; 8.6-sec, 8.6-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

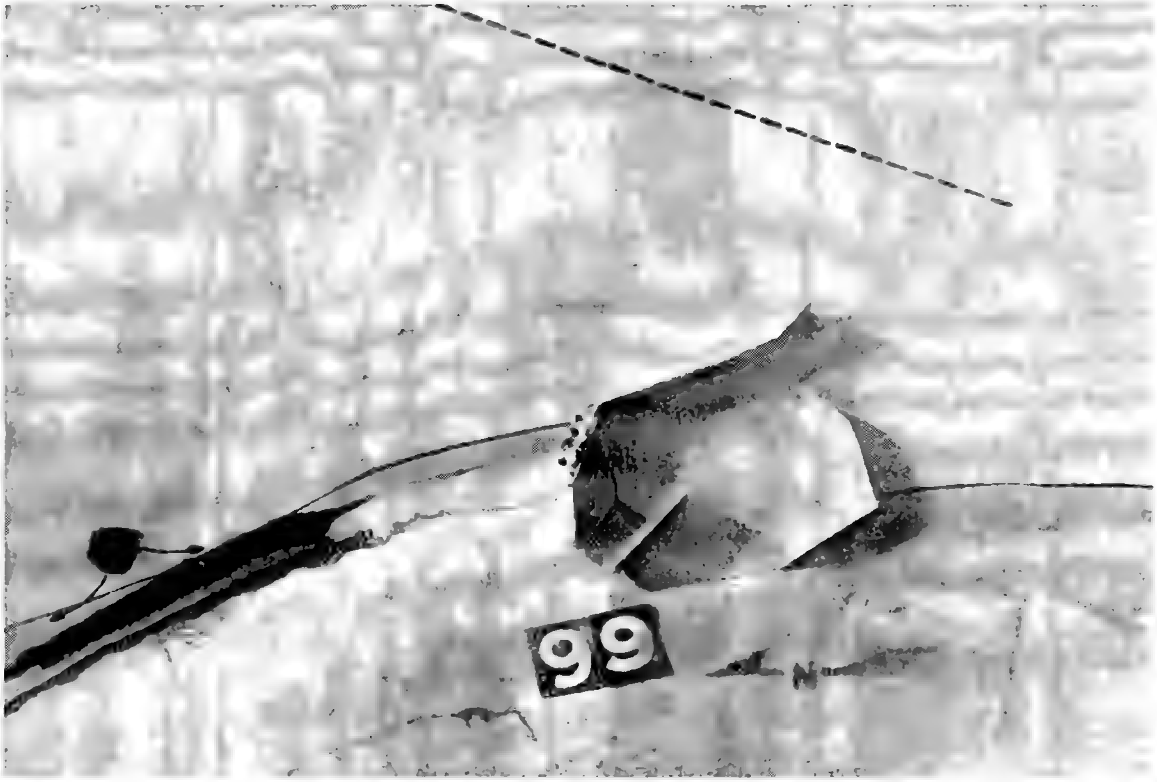



Photo 77. General movement of tracer material and subsequent deposits for Plan 9; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +1.7 ft (no riverflow conditions)

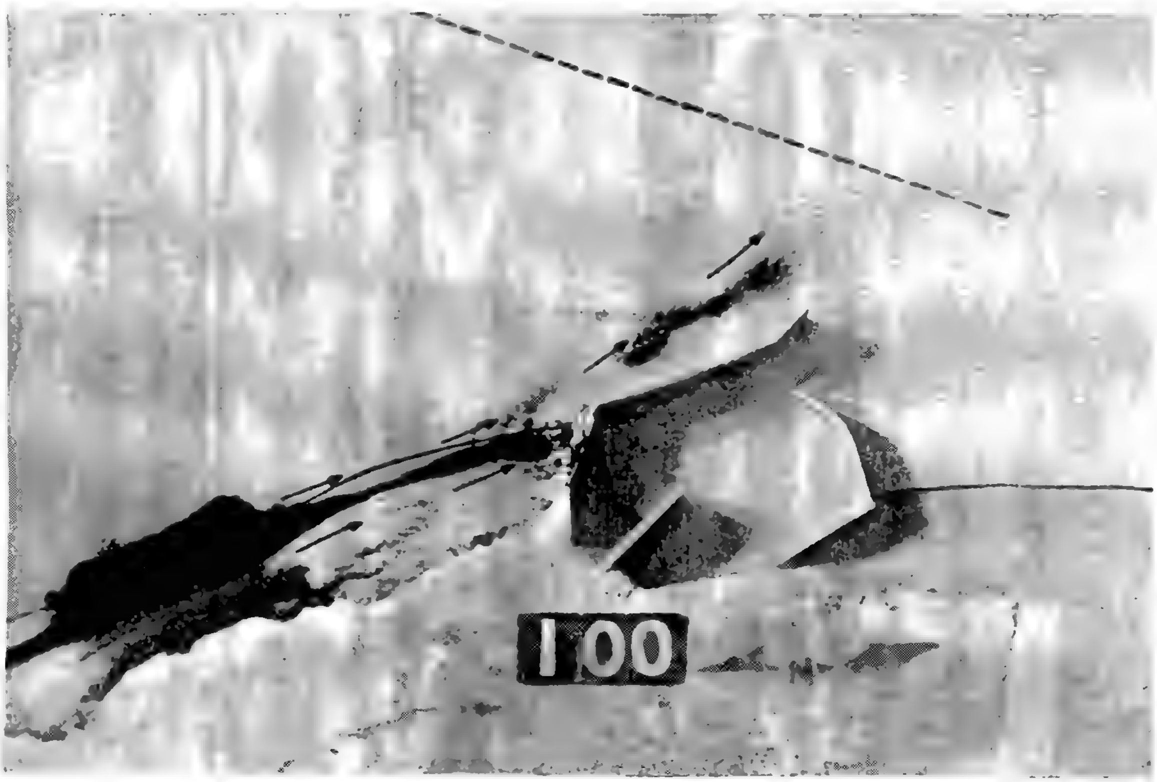



Photo 78 General movement of tracer material and subsequent deposits for Plan 9; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = + 1.7 ft (no riverflow conditions)

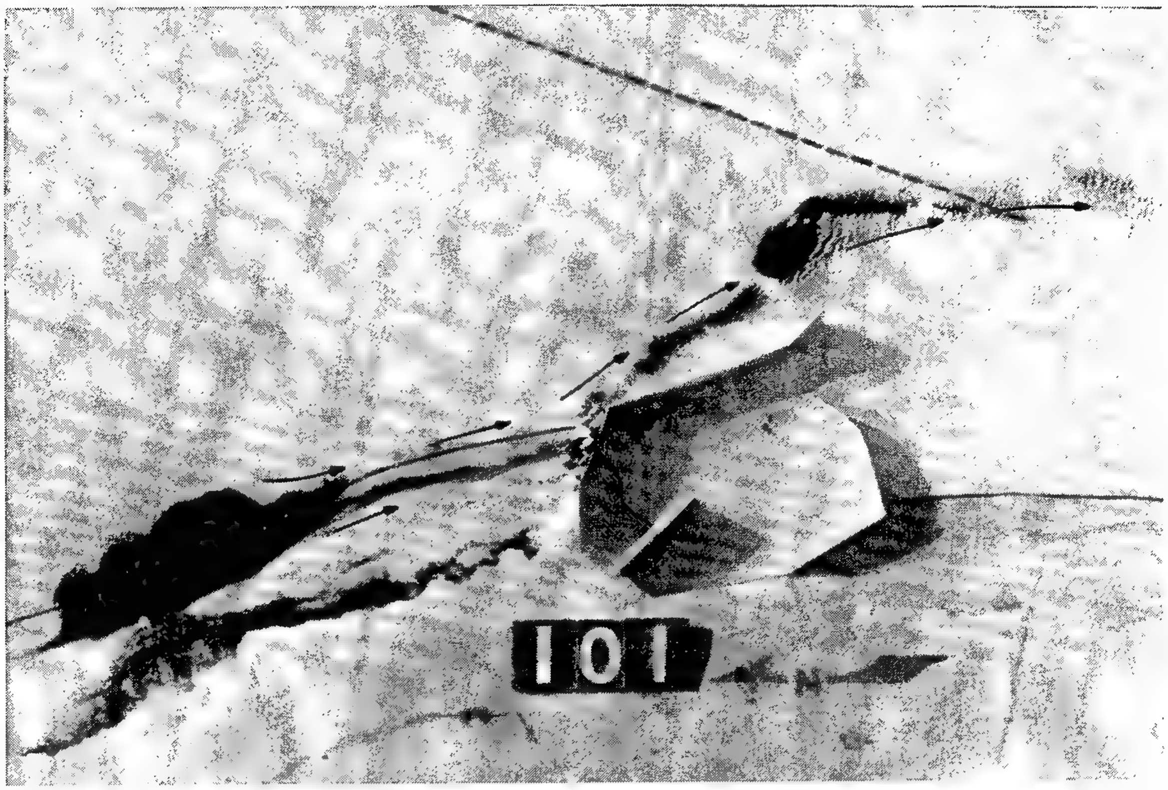



Photo 79. General movement of tracer material and subsequent deposits for Plan 9; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +1.7 ft (no riverflow conditions)

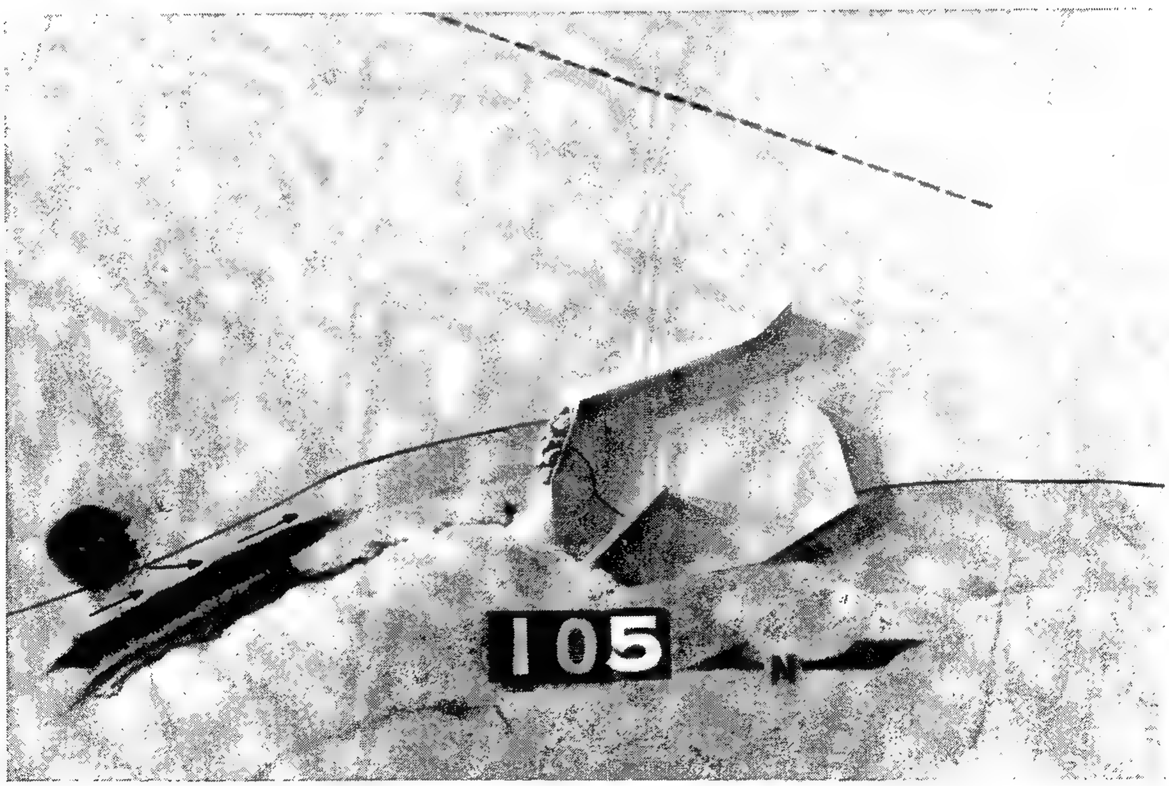



Photo 80. General movement of tracer material and subsequent deposits for Plan 9; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (no riverflow conditions)

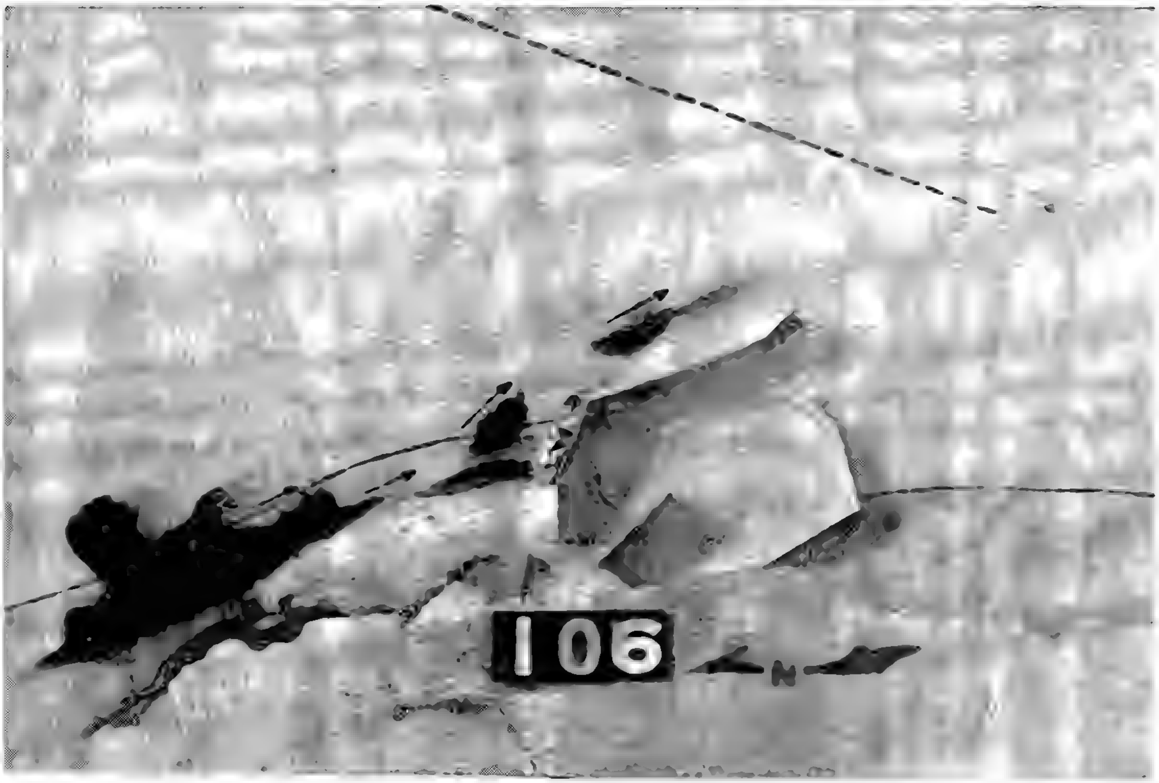



Photo 81. General movement of tracer material and subsequent deposits for Plan 9, 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +3.5 ft (no riverflow conditions)

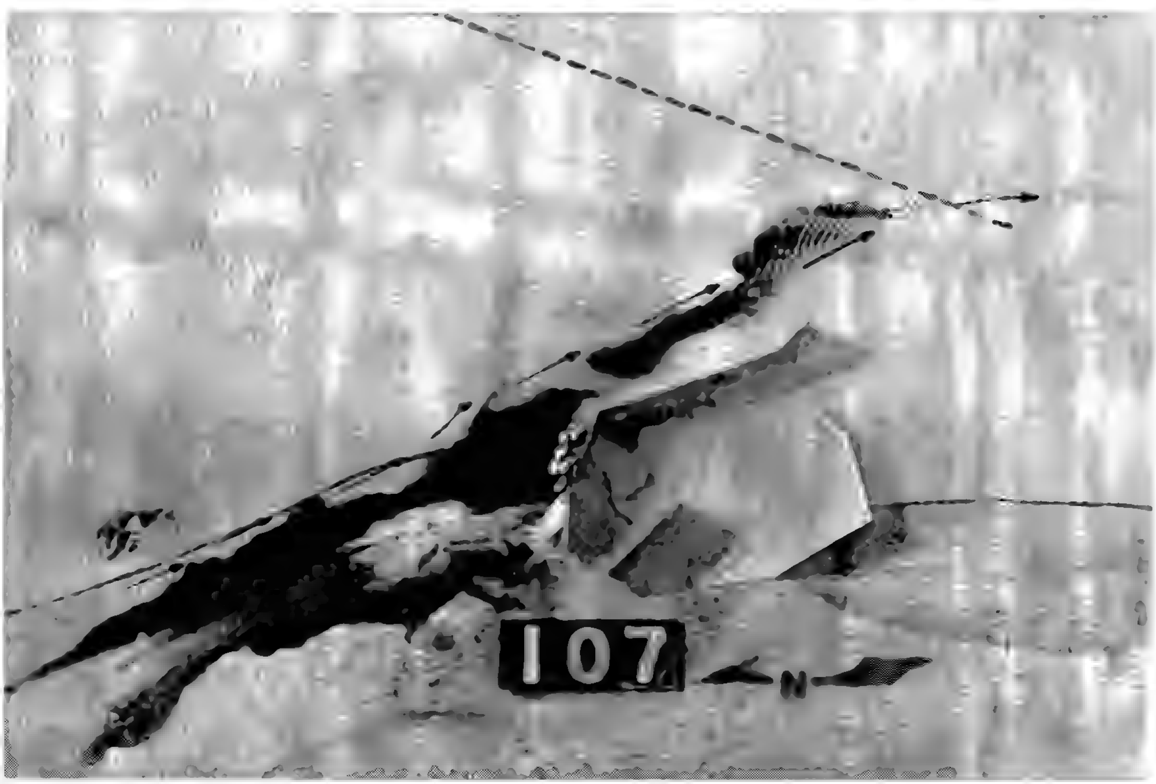



Photo 82. General movement of tracer material and subsequent deposits for Plan 9, 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +3.5 ft (no riverflow conditions)

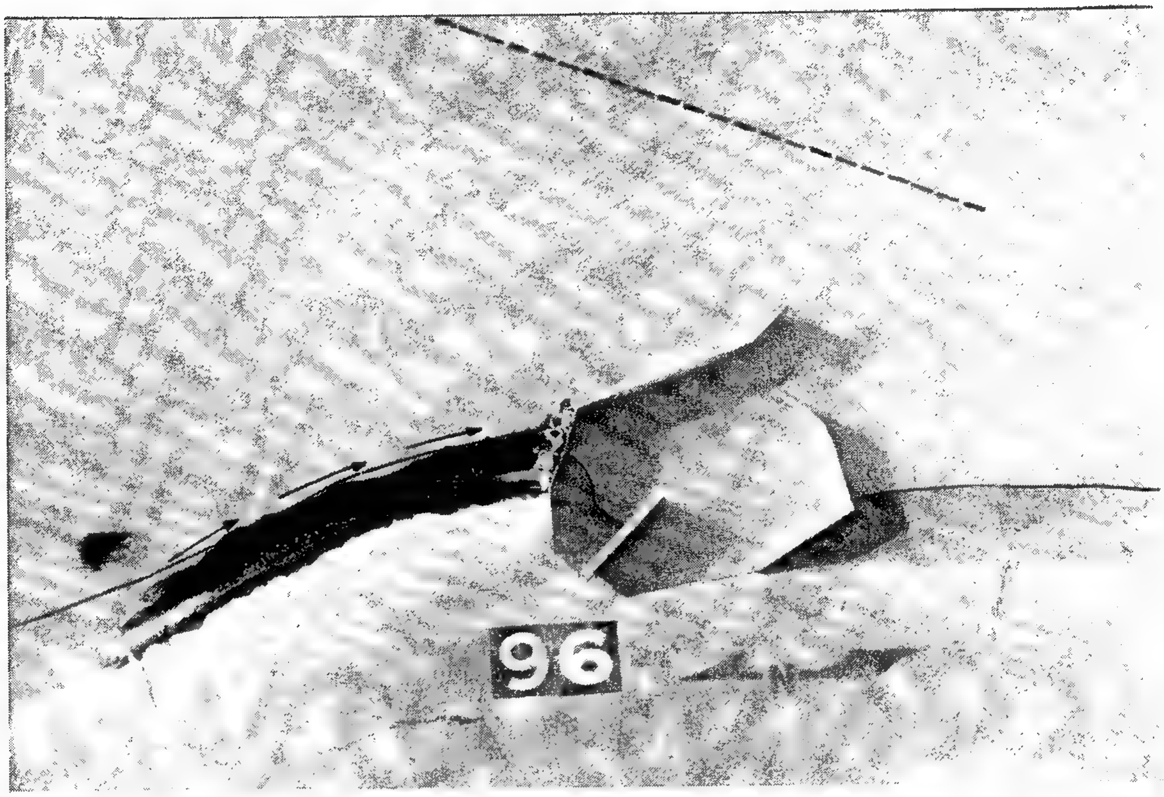



Photo 83. General movement of tracer material and subsequent deposits for Plan 9; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +1.7 ft (with riverflow conditions)

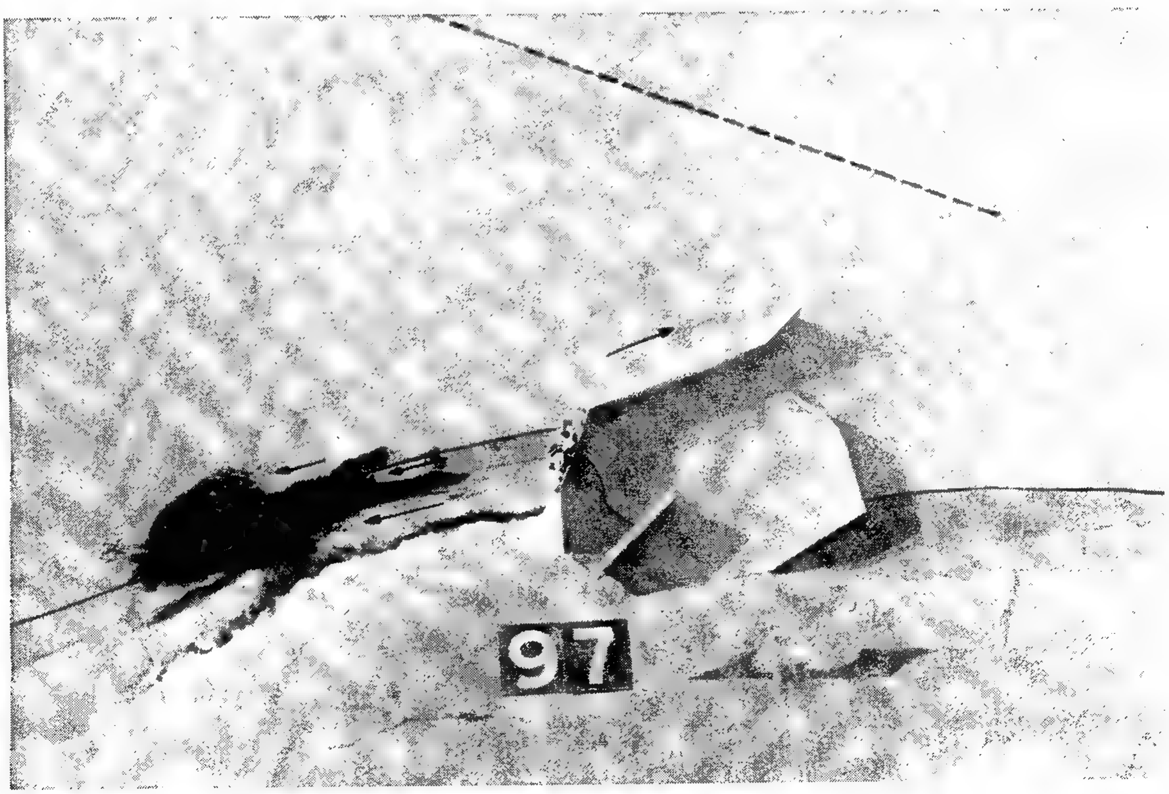



Photo 84. General movement of tracer material and subsequent deposits for Plan 9; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +1.7 ft (with riverflow conditions)

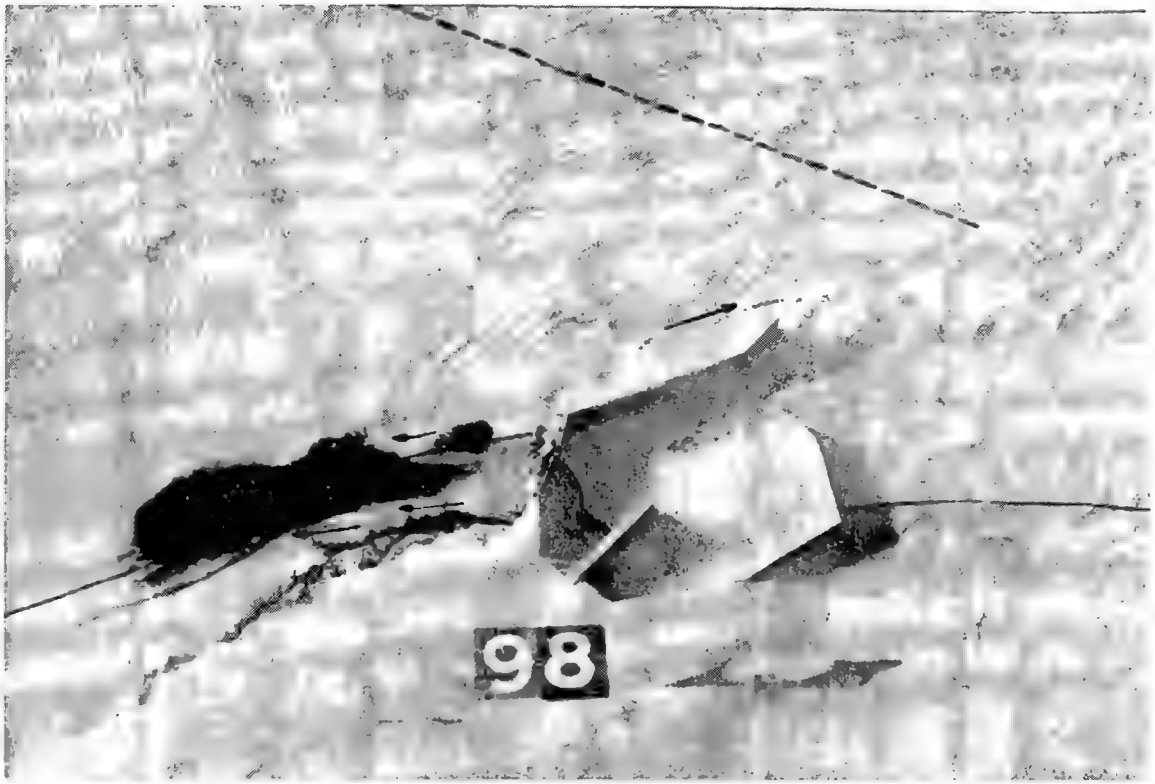



Photo 85. General movement of tracer material and subsequent deposits for Plan 9; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +1.7 ft (with riverflow conditions)

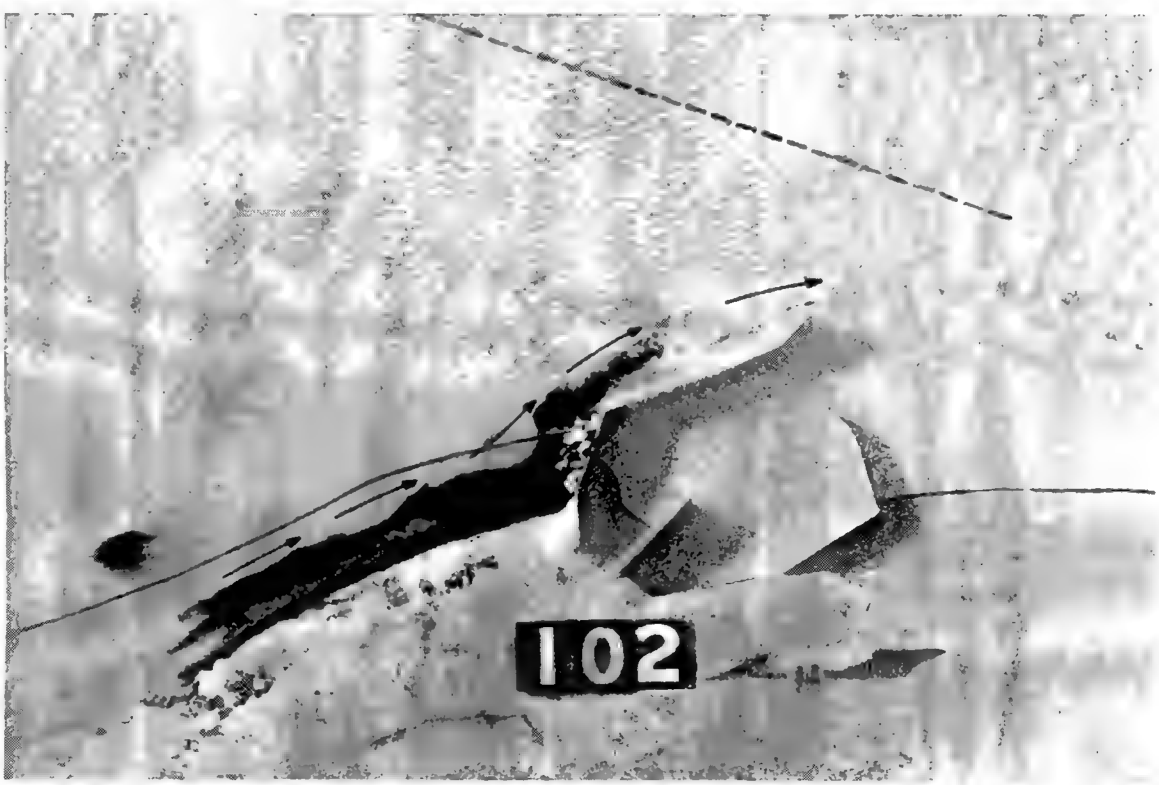



Photo 86. General movement of tracer material and subsequent deposits for Plan 9; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

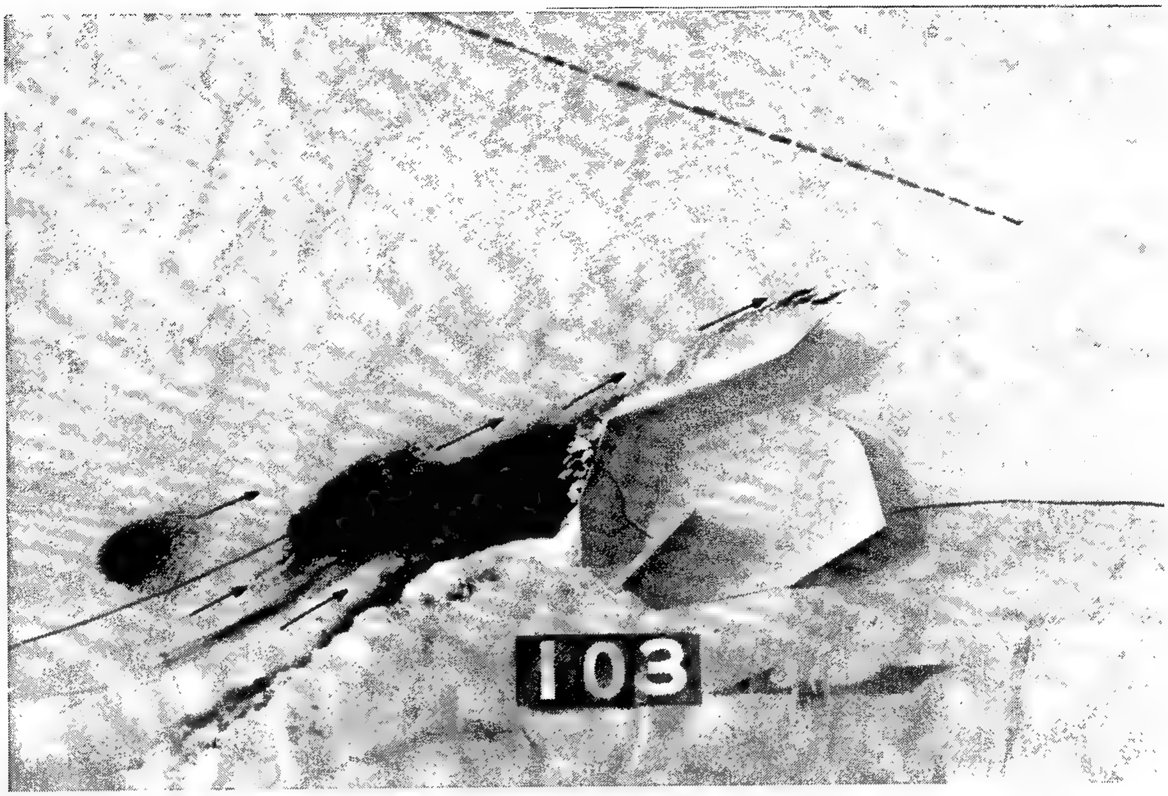



Photo 87. General movement of tracer material and subsequent deposits for Plan 9; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

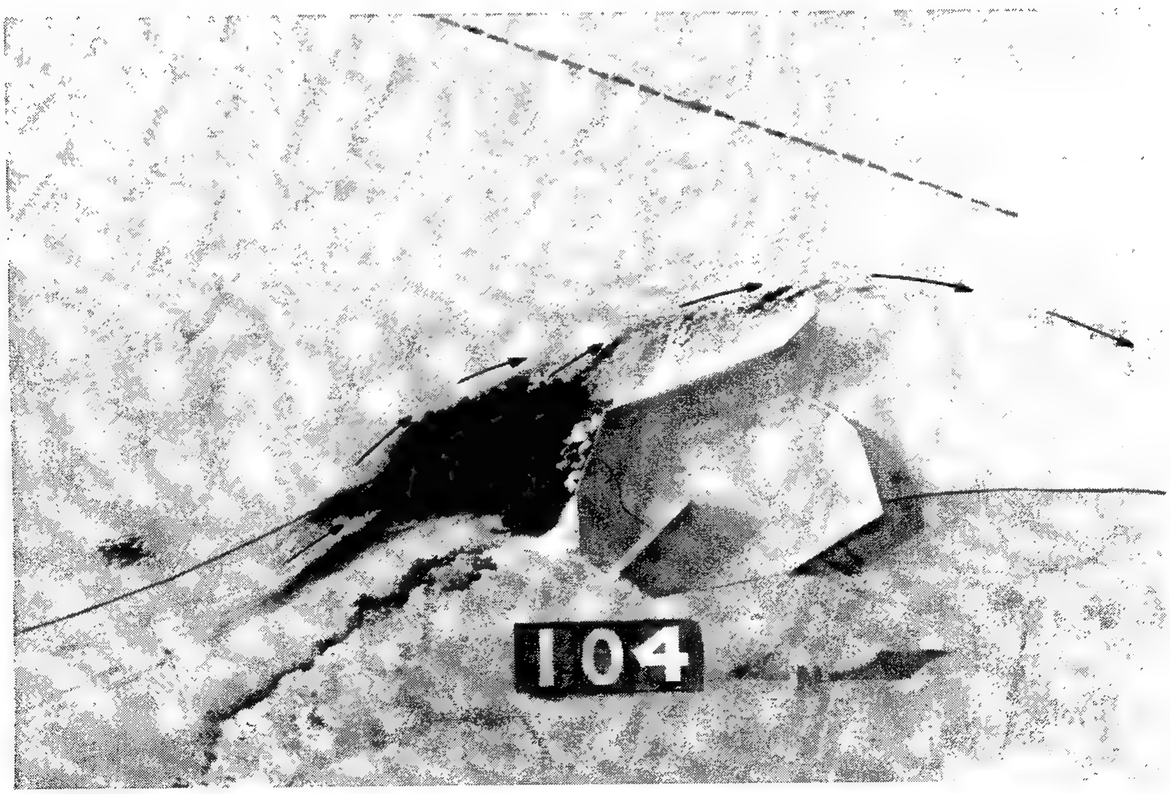



Photo 88. General movement of tracer material and subsequent deposits for Plan 9; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

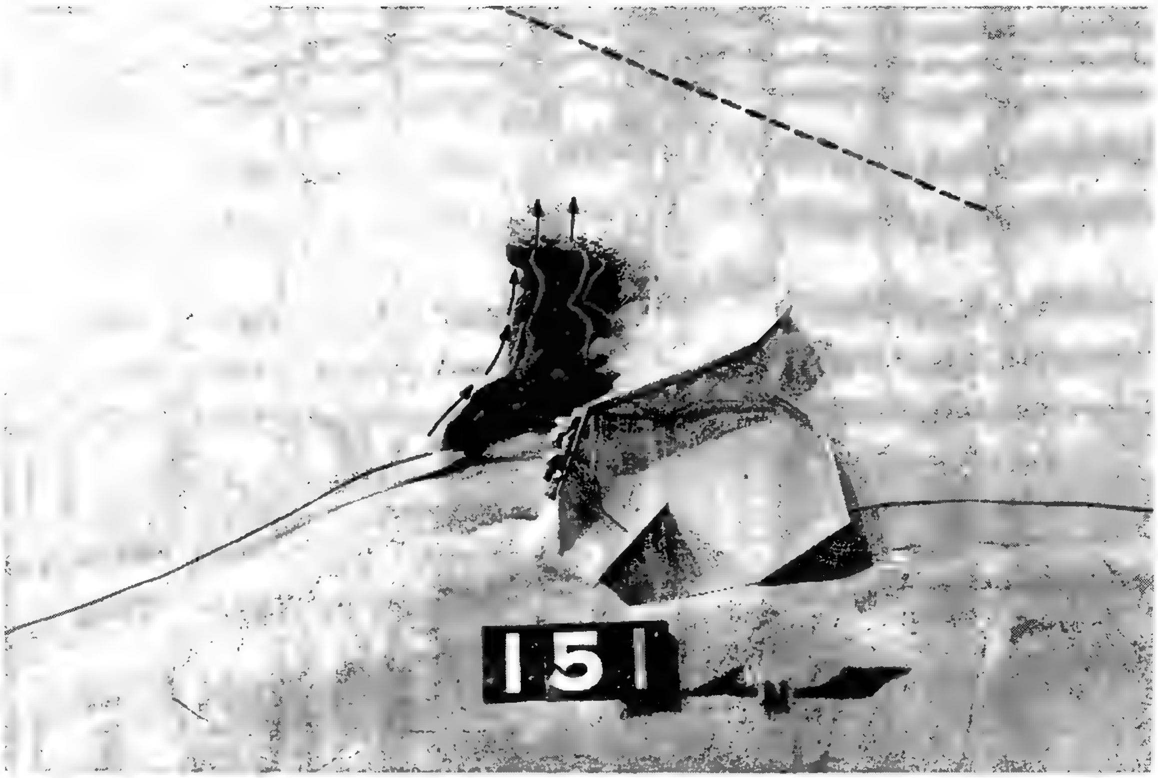



Photo 89. General movement of tracer material and subsequent deposits for Plan 9; 5.0-sec, 4.0-ft waves run for 10 min from 59 deg; swl = +1.7 ft (no riverflow conditions)


Photo 90. General movement of tracer material and subsequent deposits for Plan 9; 5.0-sec, 4.0-ft waves run for 10 min, and 6.0-sec, 6.1-ft waves run for 5 min from 59 deg; swl = +1.7 ft (no riverflow conditions)

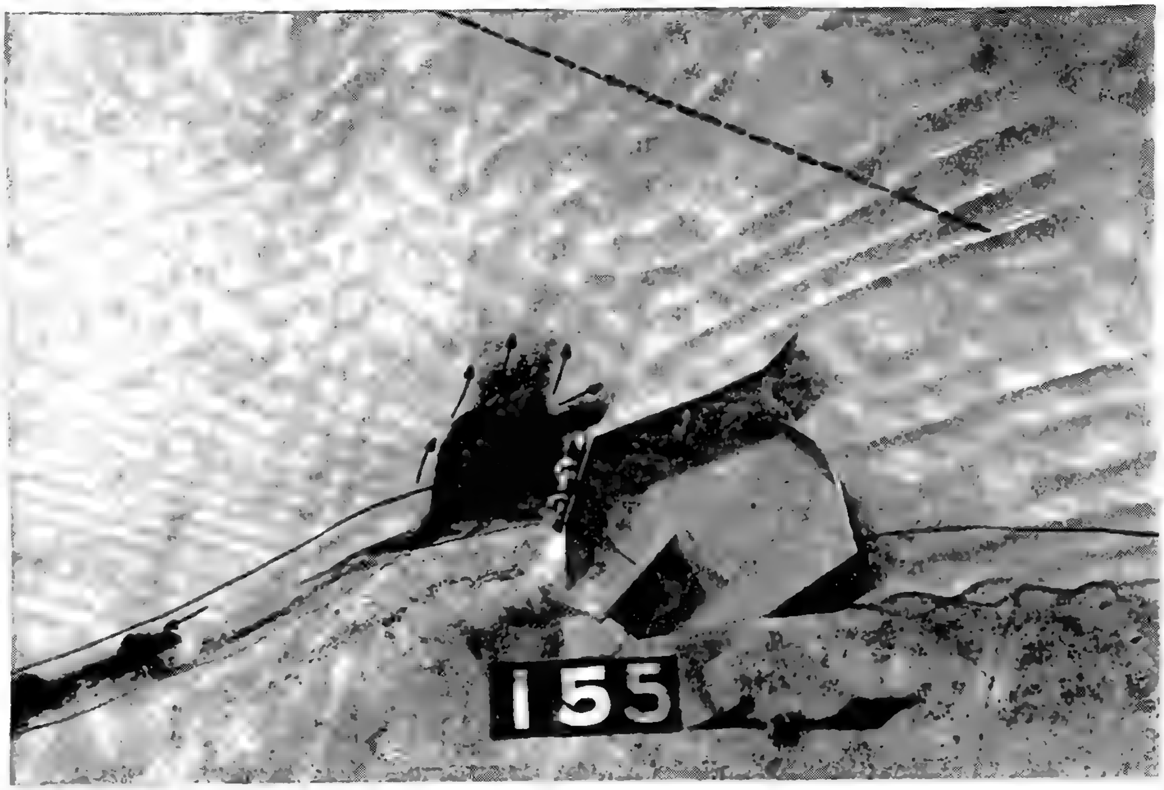



Photo 91. General movement of tracer material and subsequent deposits for Plan 9; 5.0-sec, 4.0-ft waves run for 10 min from 59 deg; swl = +3.5 ft (no riverflow conditions)

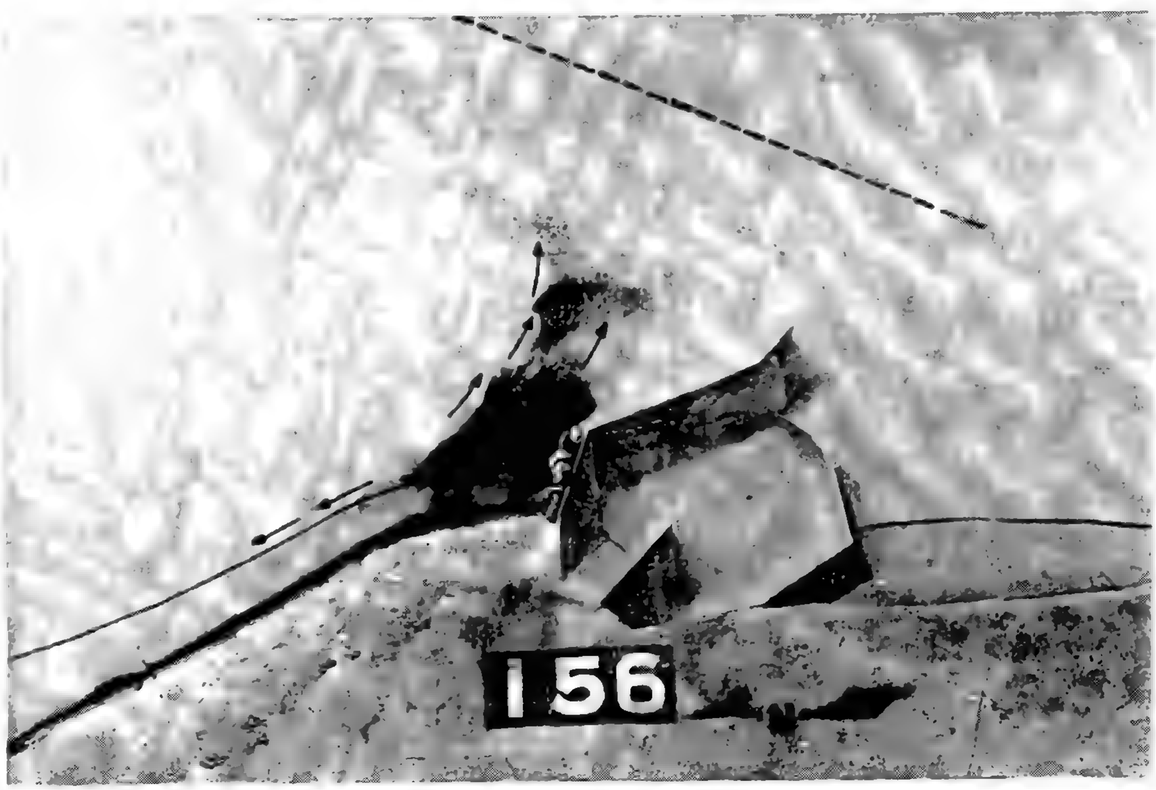



Photo 92. General movement of tracer material and subsequent deposits for Plan 9; 5.0-sec, 4.0-ft waves run for 10 min, and 6.0-sec, 6.1-ft waves run for 5 min from 59 deg; swl = +3.5 ft (no riverflow conditions)

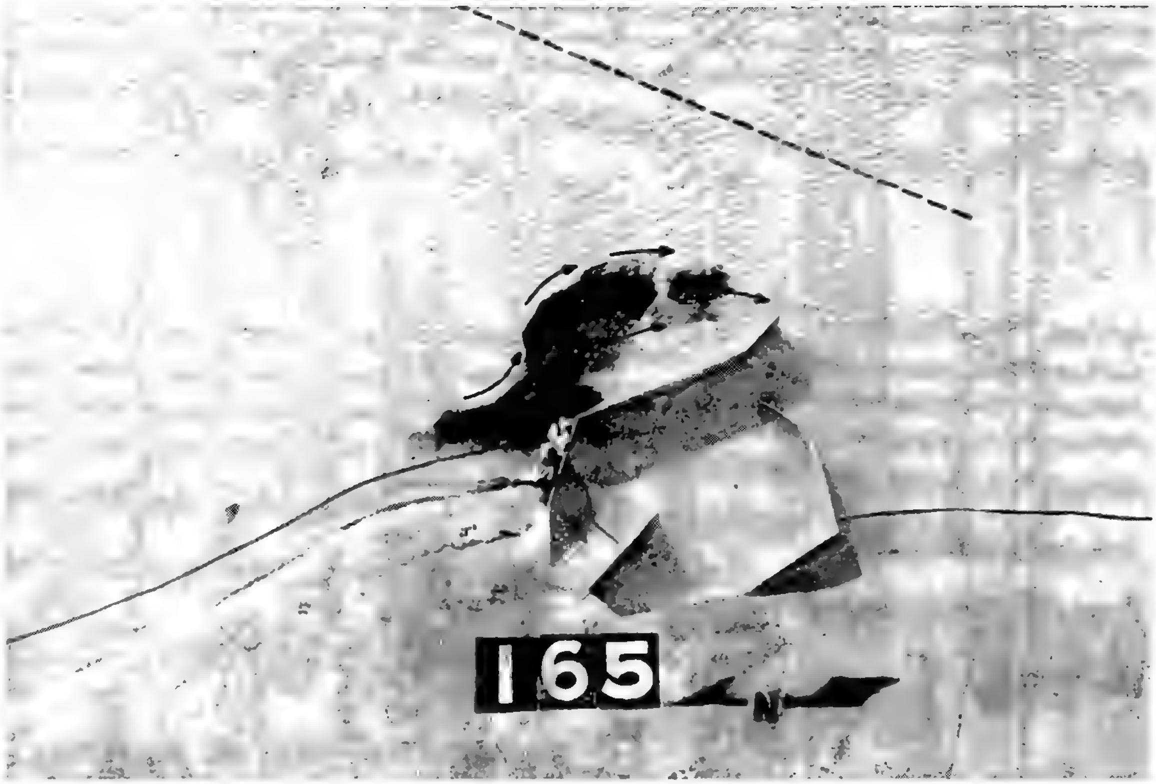



Photo 93. General movement of tracer material and subsequent deposits for Plan 9; 5.0-sec, 4.0-ft waves run for 10 min from 59 deg; swl = +1.7 ft (with riverflow conditions)

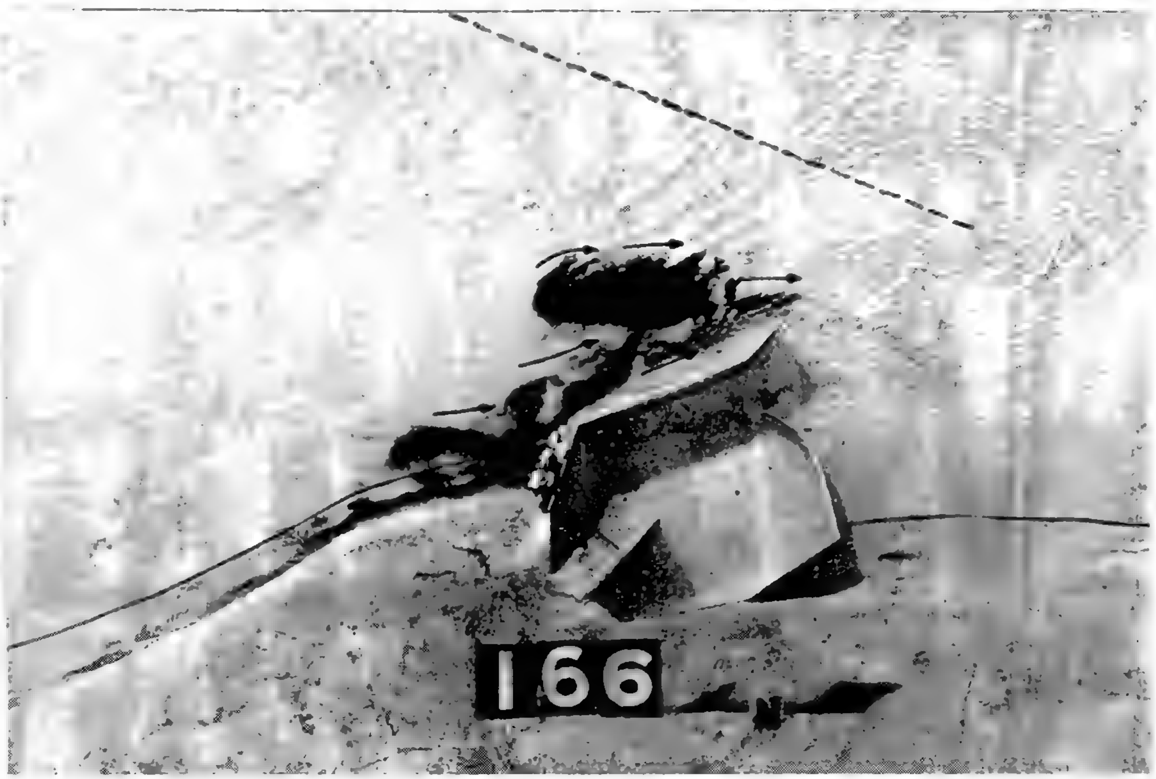



Photo 94. General movement of tracer material and subsequent deposits for Plan 9; 5.0-sec, 4.0-ft waves run for 10 min, and 6.0-sec, 6.1-ft waves run for 5 min from 59 deg; swl = +1.7 ft (with riverflow conditions)

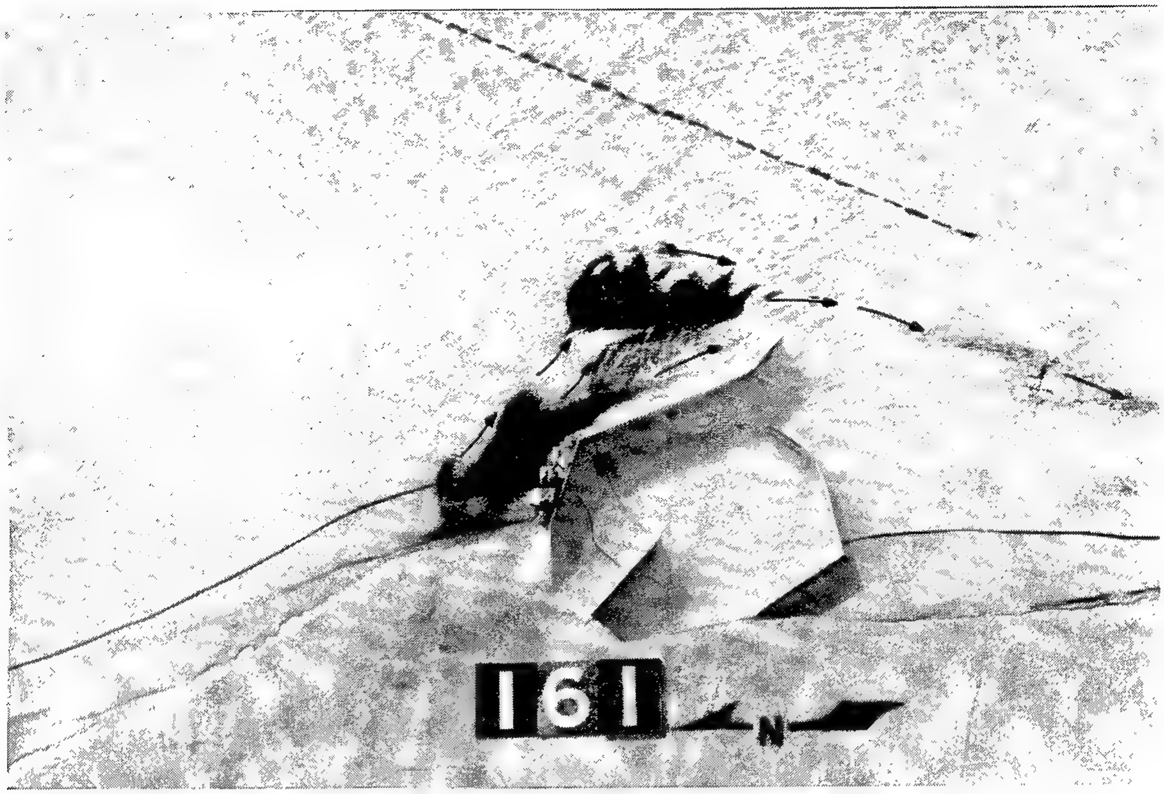



Photo 95. General movement of tracer material and subsequent deposits for Plan 9; 5.0-sec, 4.0-ft waves run for 10 min from 59 deg; swl = +3.5 ft (with riverflow conditions)

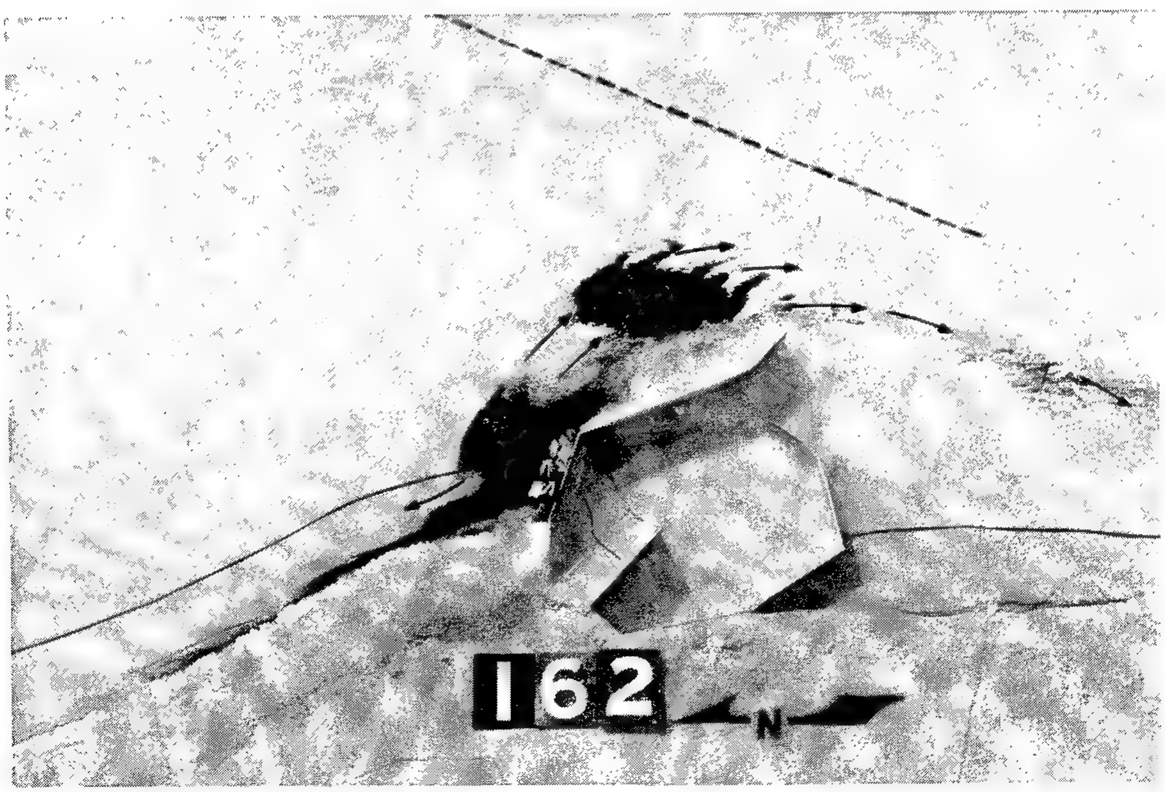



Photo 96. General movement of tracer material and subsequent deposits for Plan 9; 5.0-sec, 4.0-ft waves run for 10 min, and 6.0-sec, 6.1-ft waves run for 5 min from 59 deg; swl = +3.5 ft (with riverflow conditions)

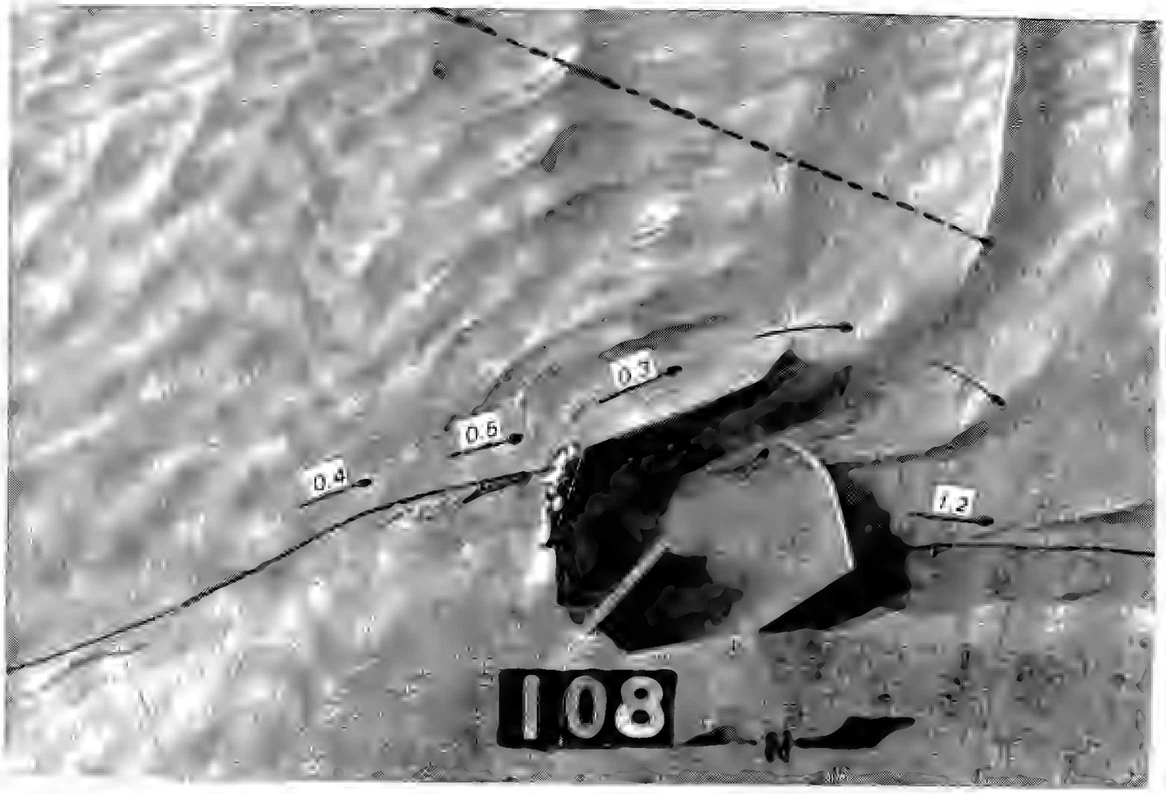



Photo 97. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 6.0-sec, 4.0-ft waves from 11 deg; swl = +1.7 ft (no riverflow conditions)

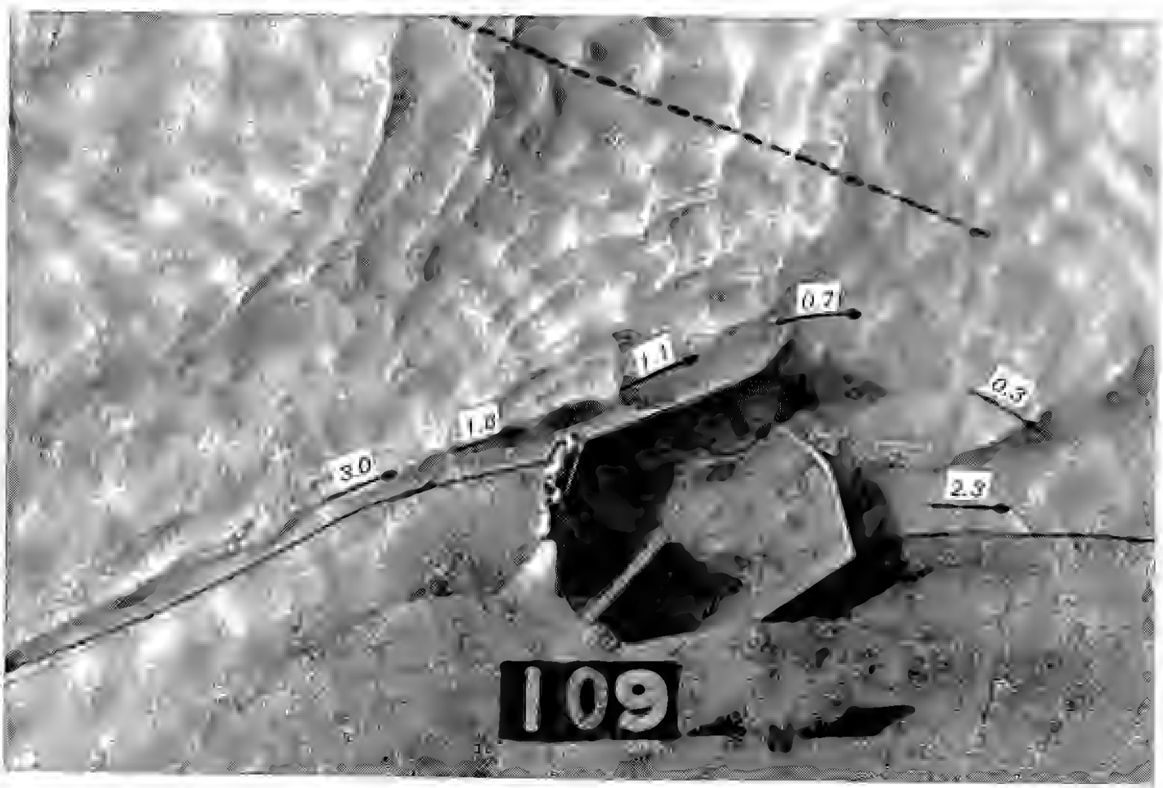



Photo 98. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 8.6-sec, 8.6-ft waves from 11 deg; swl = +1.7 ft (no riverflow conditions)

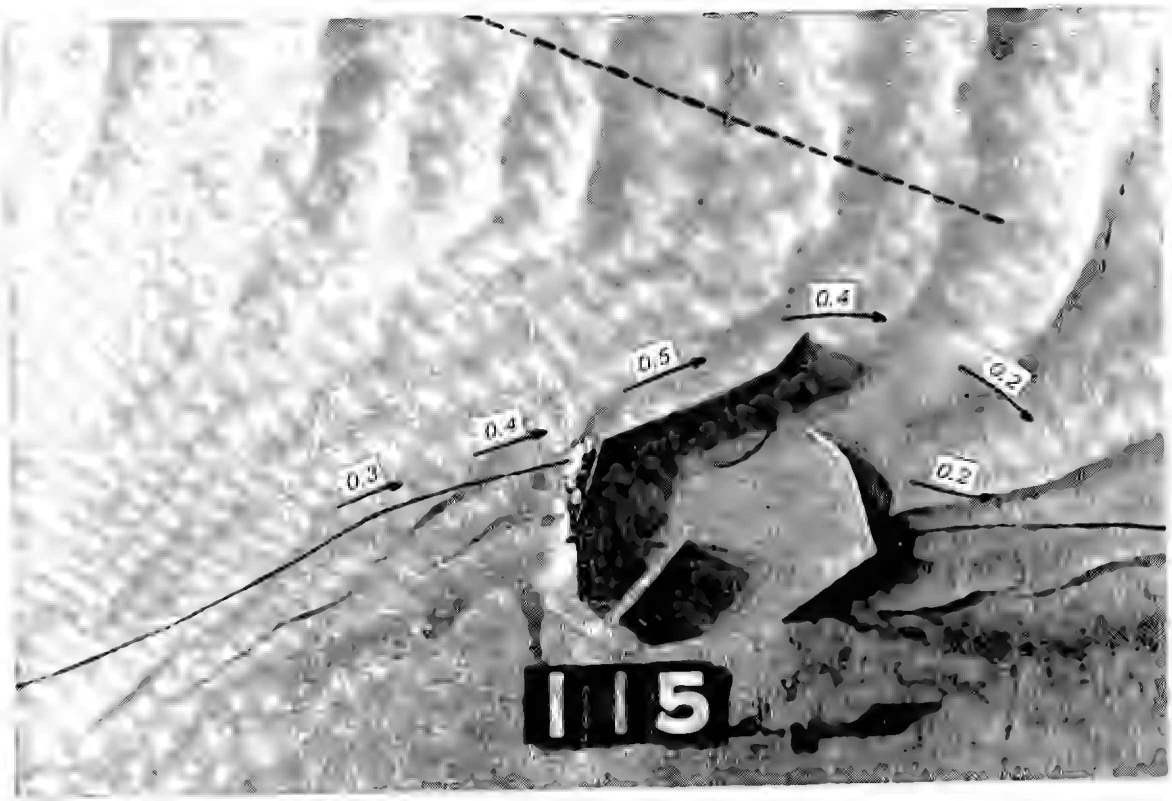



Photo 99. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 6.0-sec, 4.0-ft waves from 11 deg; swl = +3.5 ft (no riverflow conditions)

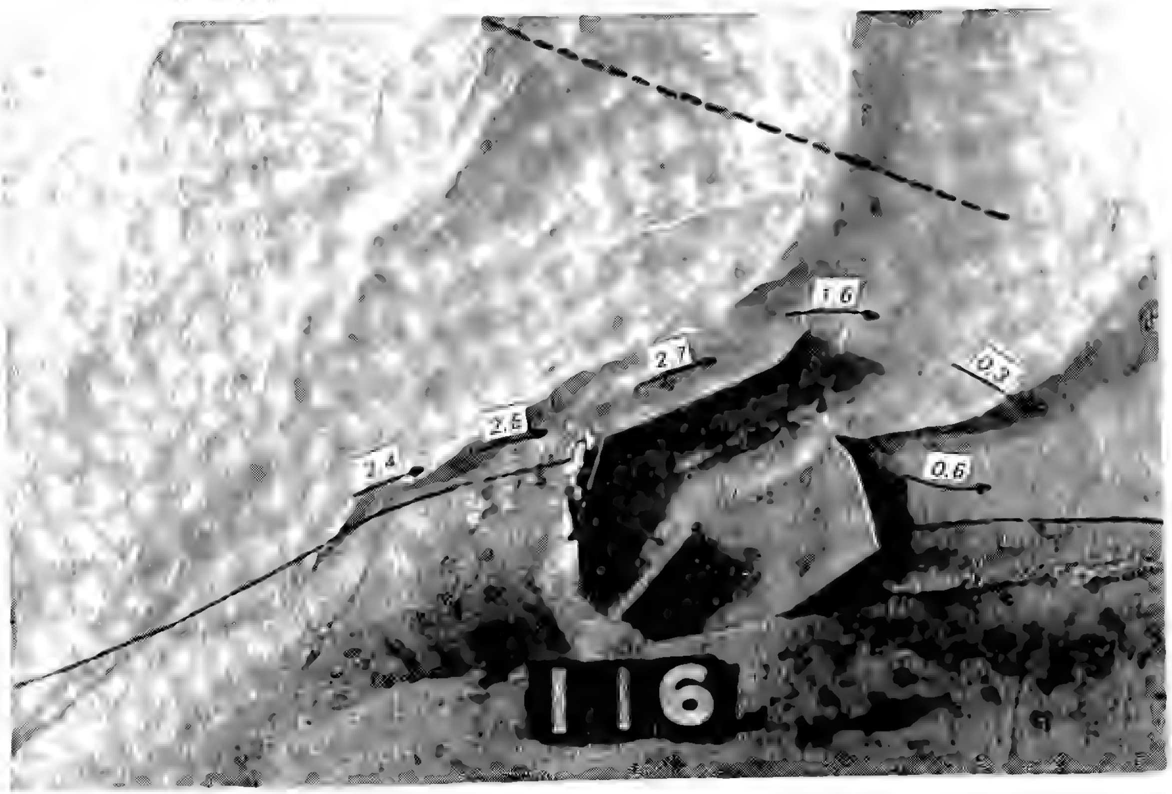



Photo 100. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 8.6-sec, 8.6-ft waves from 11 deg; swl = +3.5 ft (no riverflow conditions)

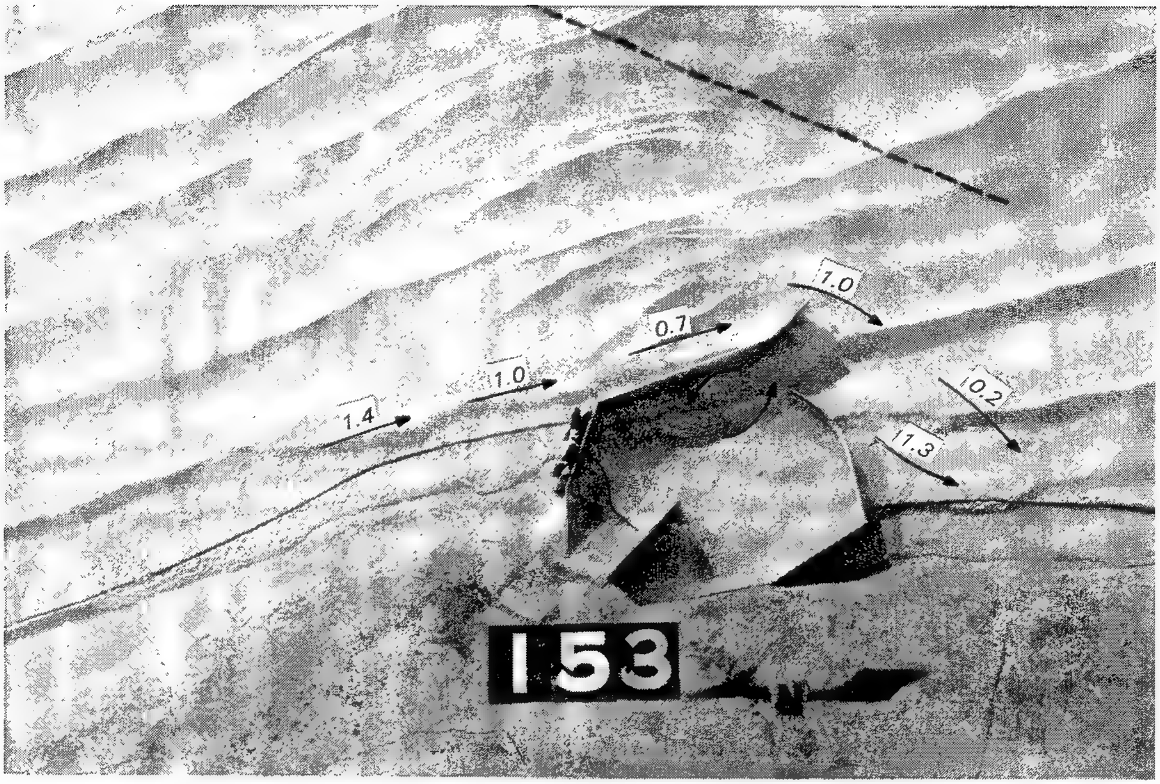



Photo 101. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 5.0-sec, 4.0-ft waves from 59 deg; swl = +1.7 ft (no riverflow conditions)

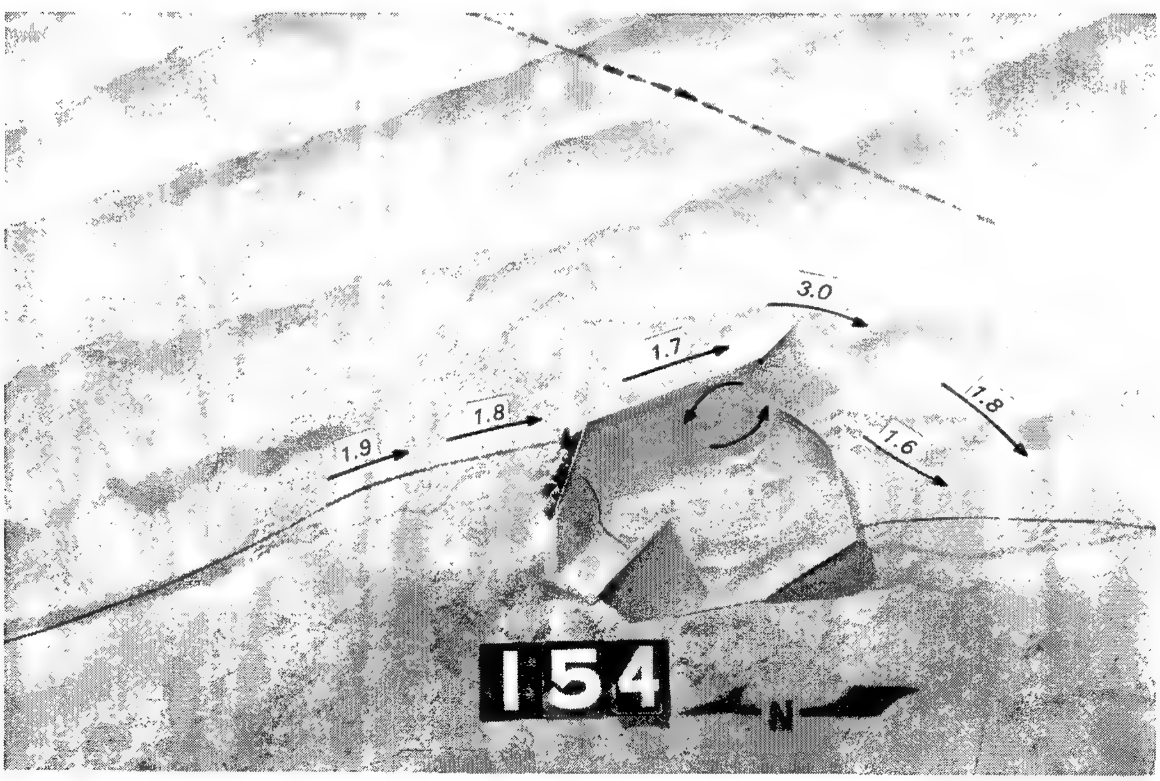



Photo 102. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 6.5-sec, 7.7-ft waves from 59 deg; swl = +1.7 ft (no riverflow conditions)

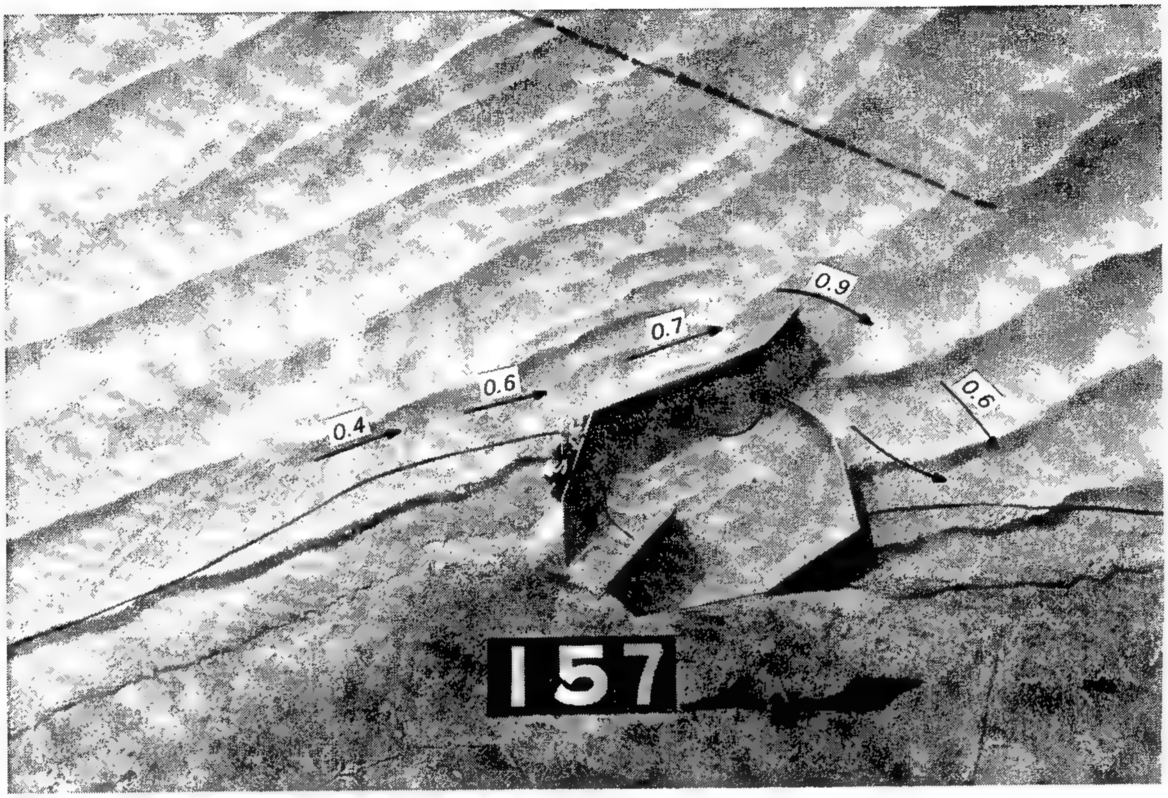



Photo 103. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 5.0-sec, 4.0-ft waves from 59 deg; swl = +3.5 ft (no riverflow conditions)

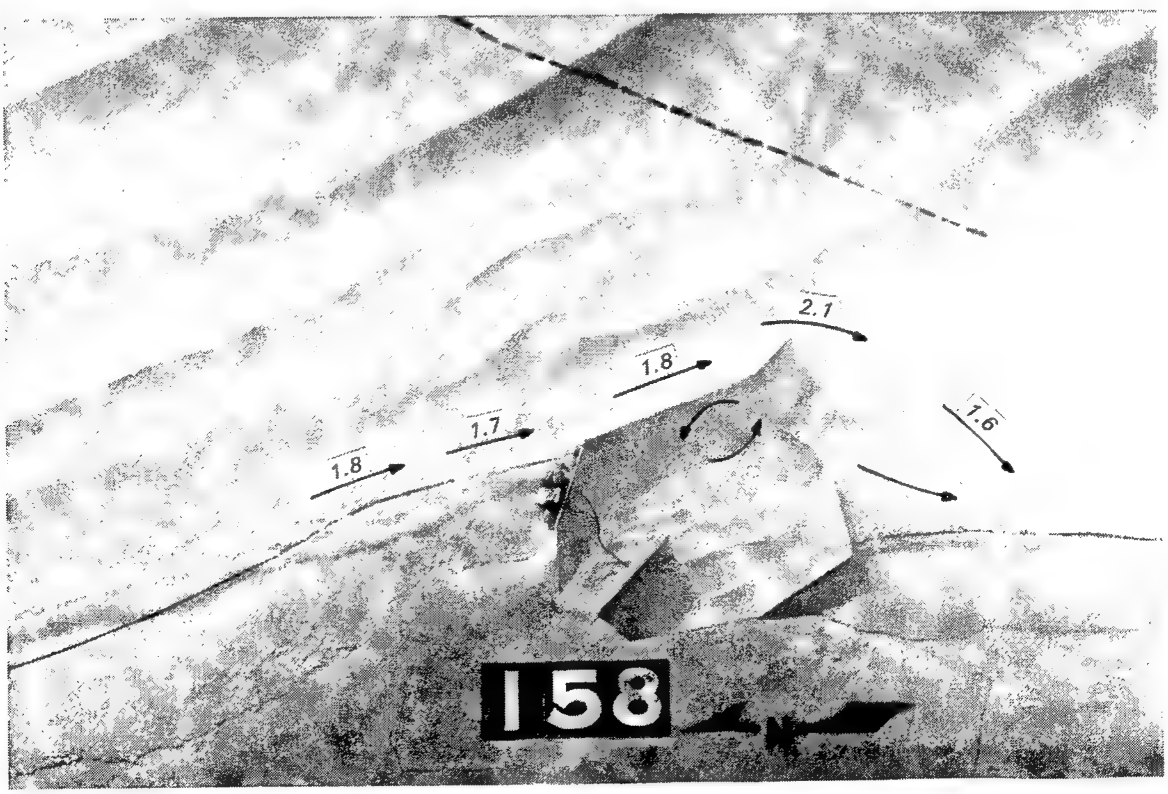



Photo 104. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 6.5-sec, 7.7-ft waves from 59 deg; swl = +3.5 ft (no riverflow conditions)

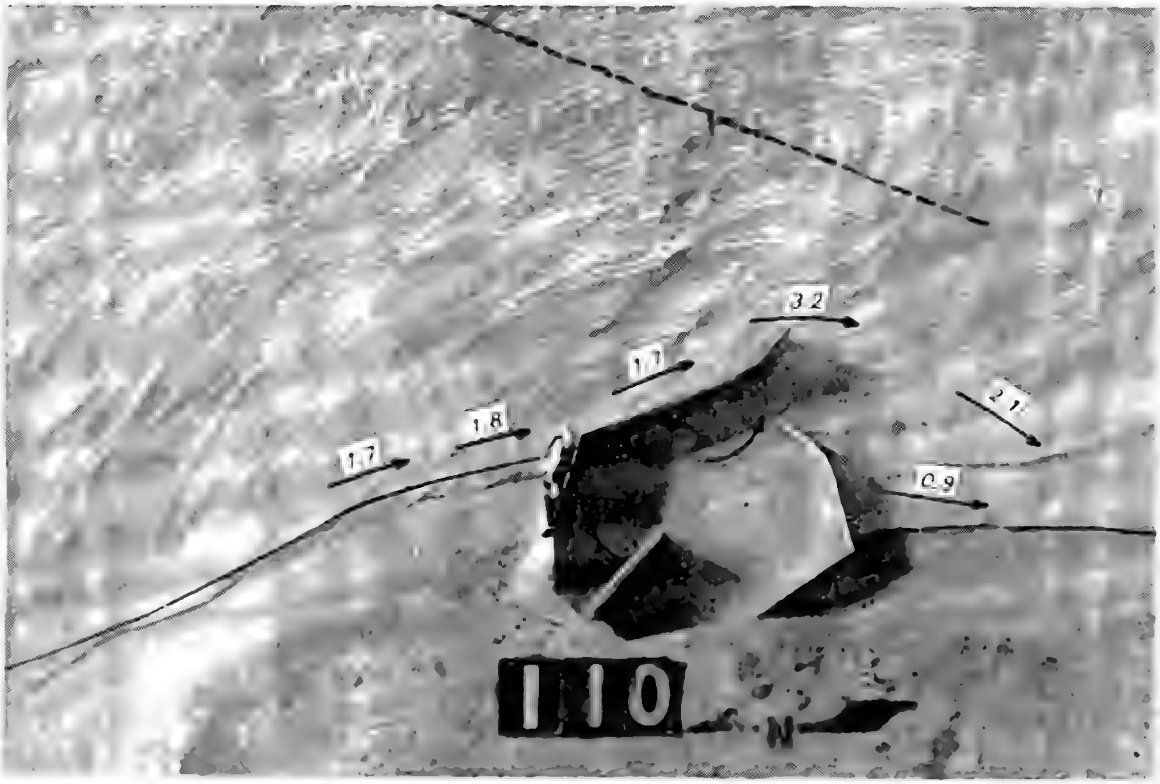



Photo 105 Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9, 6.0-sec, 4.0-ft waves from 11 deg, swl = +1.7 ft (with riverflow conditions)

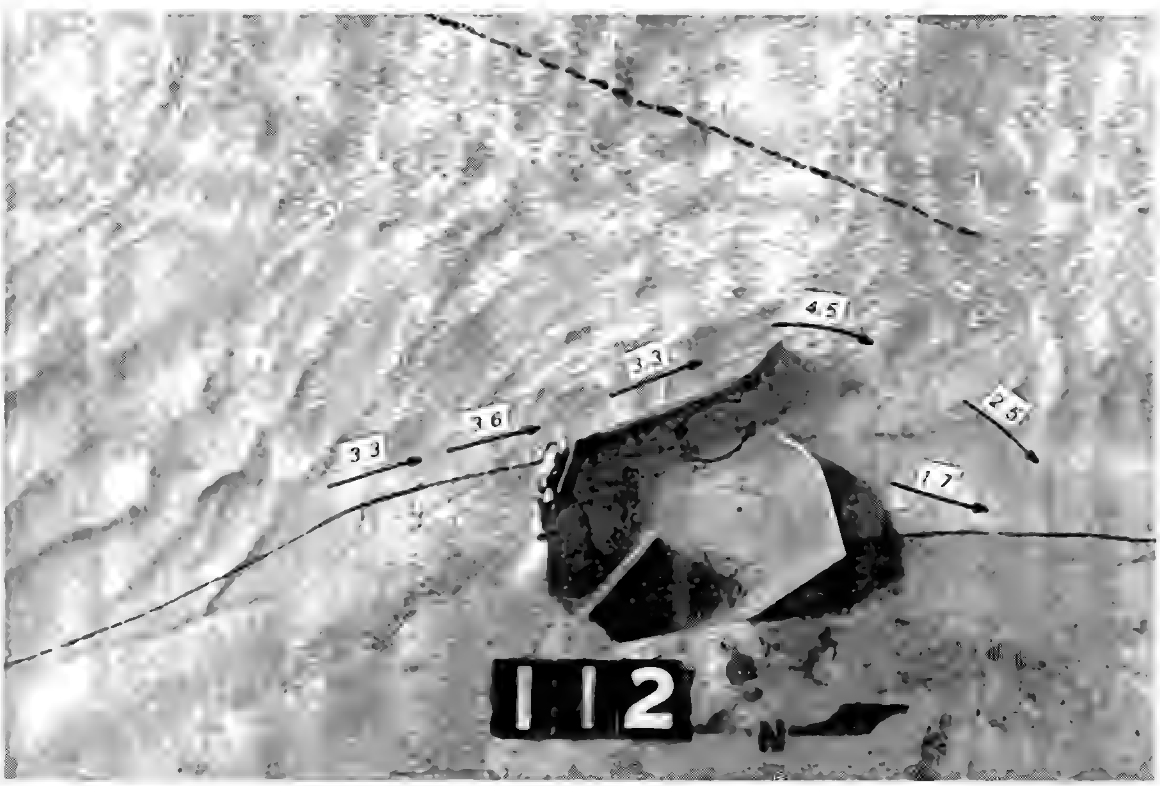



Photo 106 Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 8.6-sec, 8.6-ft waves from 11 deg; swl = +1.7 ft (with riverflow conditions)

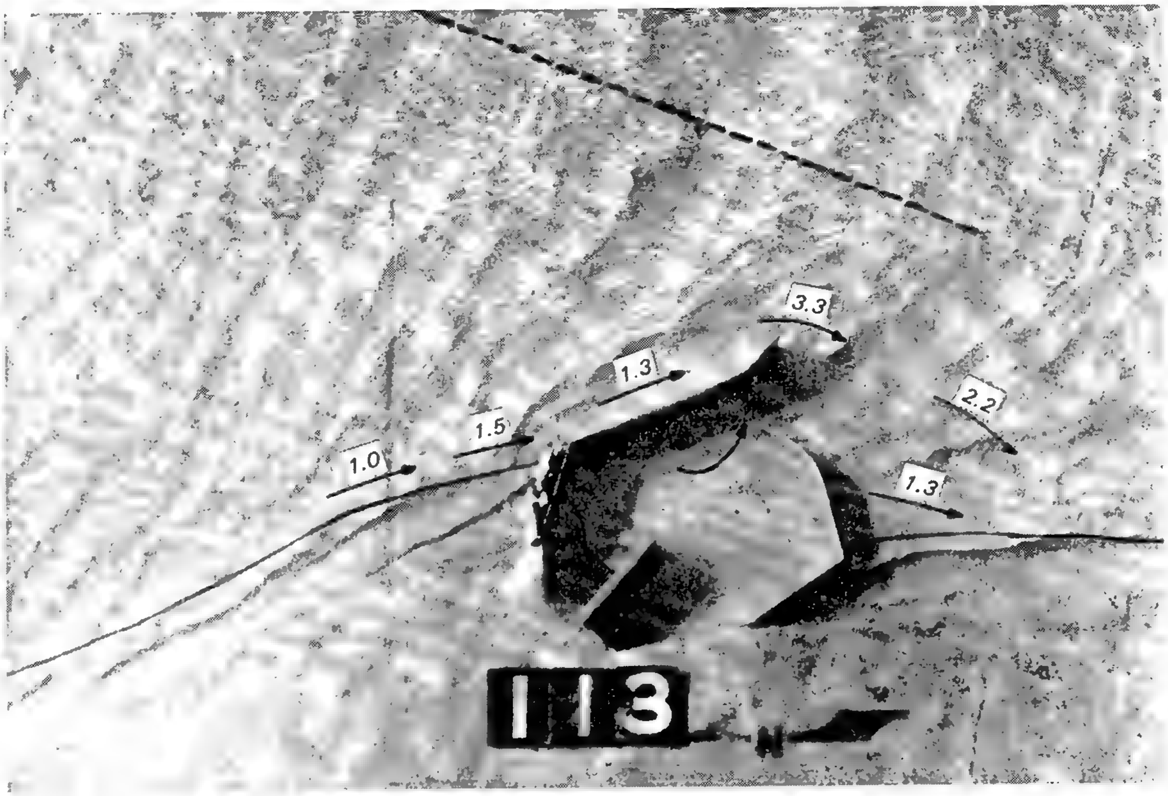



Photo 107. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 6.0-sec, 4.0-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

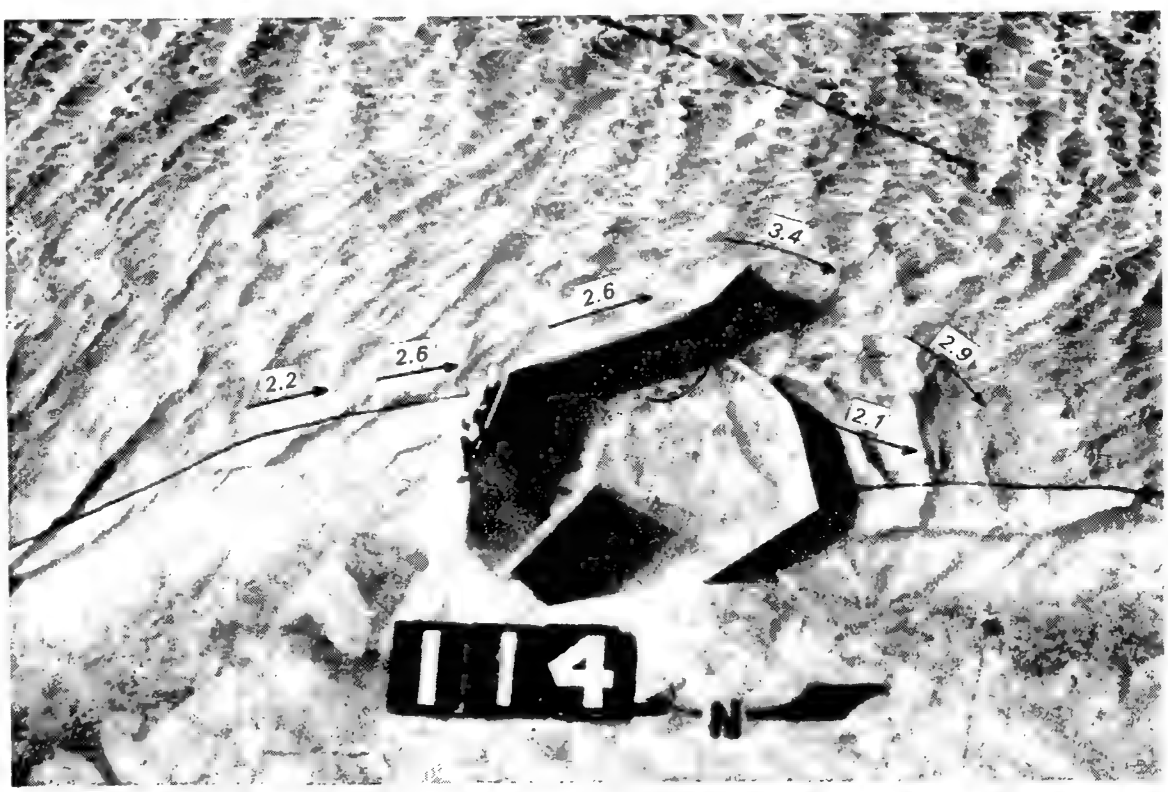



Photo 108. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 8.6-sec, 8.6-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

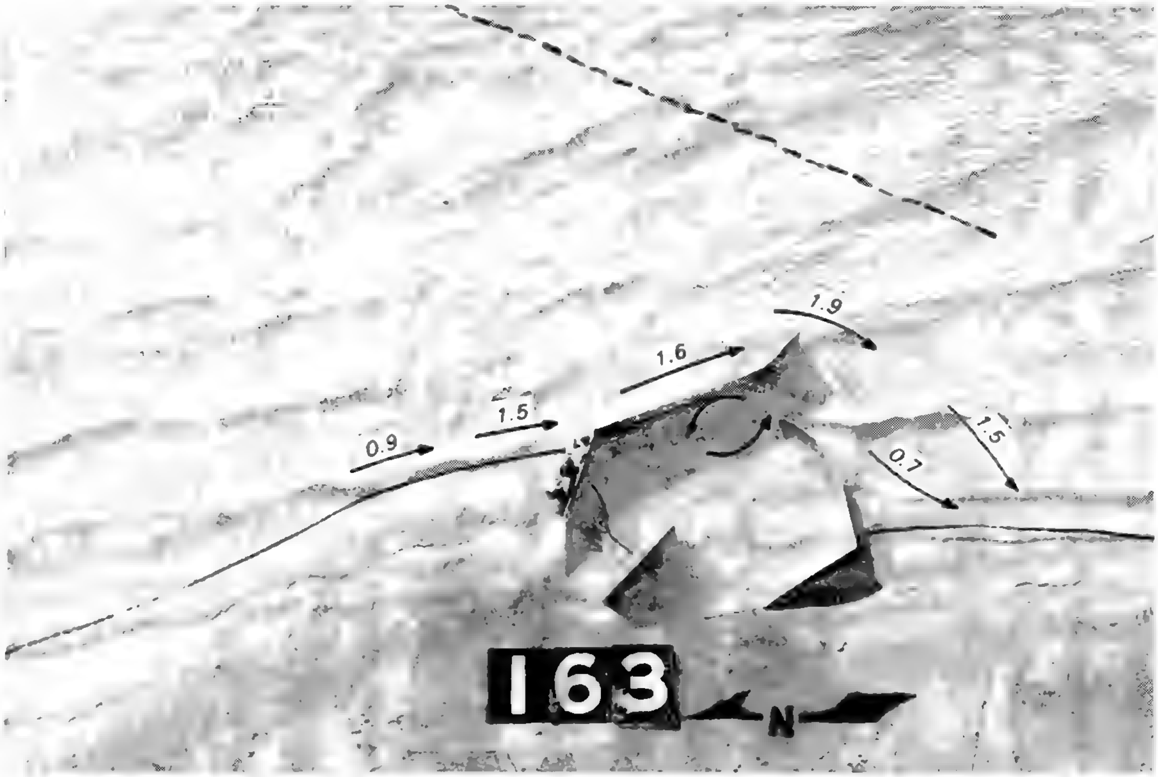



Photo 109. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 5.0-sec, 4.0-ft waves from 59 deg; swl = +1.7 ft (with riverflow conditions)

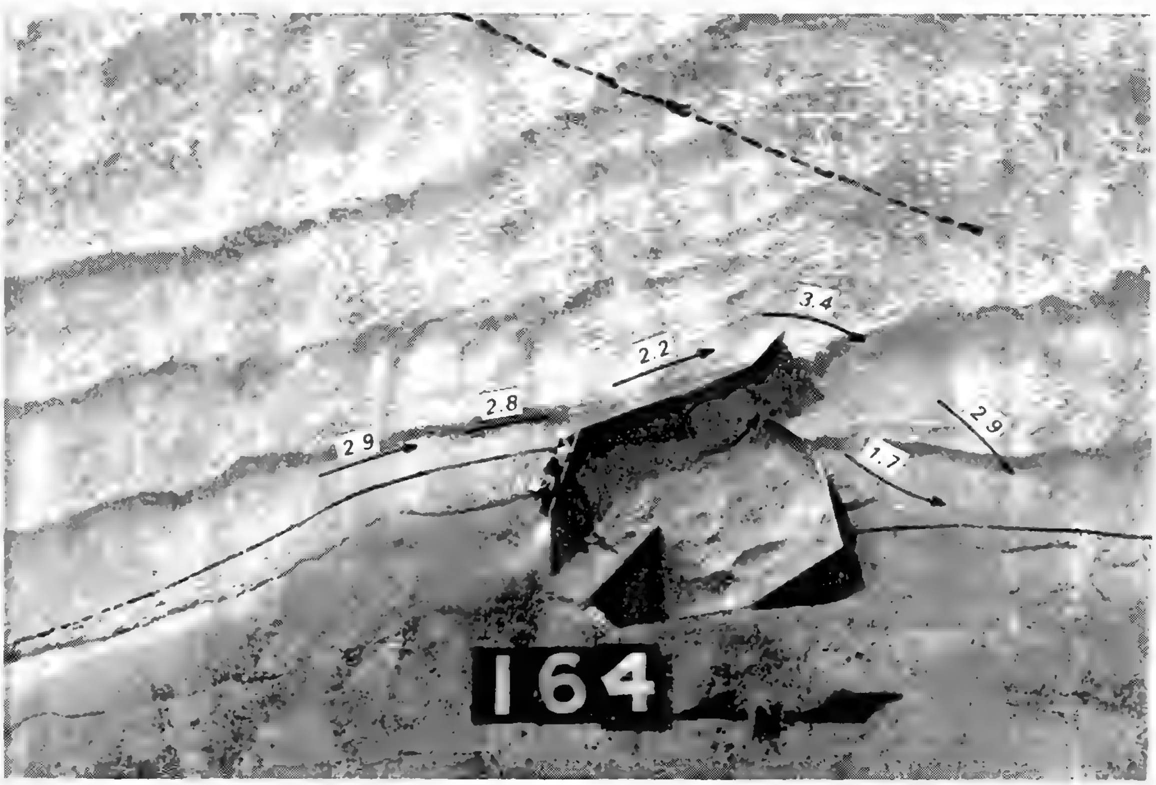



Photo 110. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 6.5-sec, 7.7-ft waves from 59 deg; swl = +1.7 ft (with riverflow conditions)

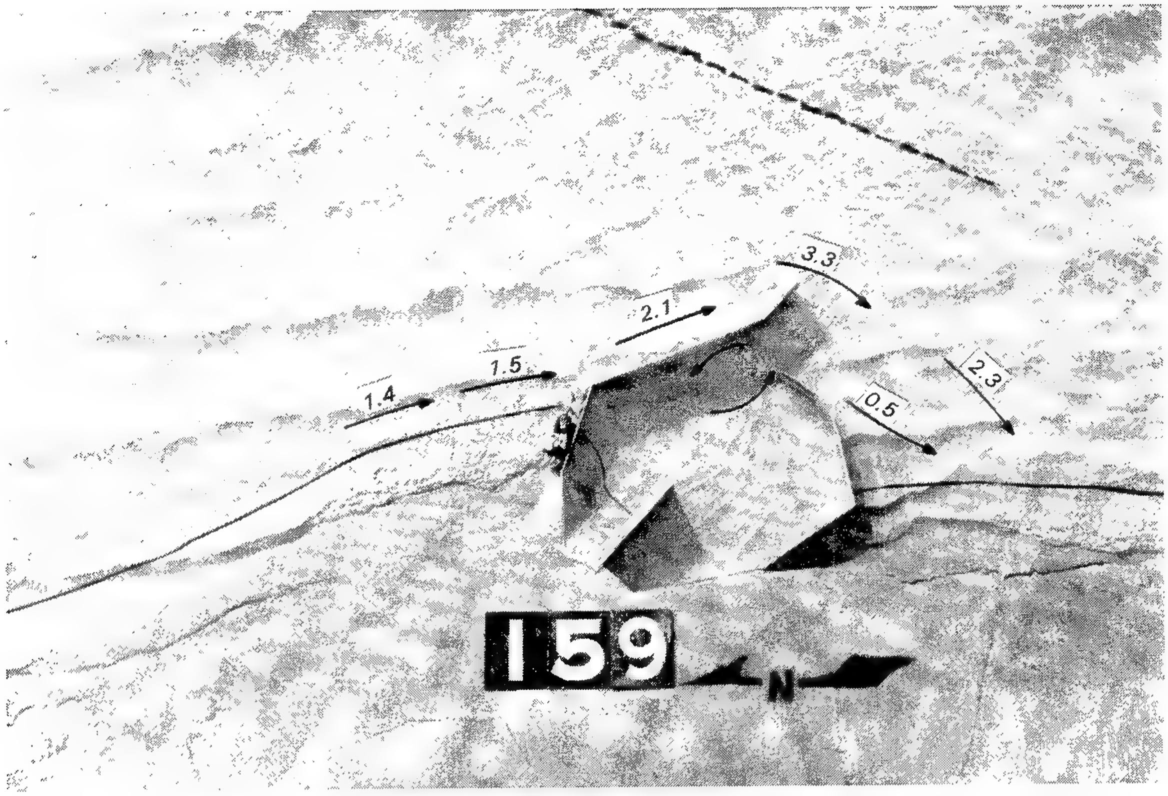



Photo 111. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 5.0-sec, 4.0-ft waves from 59 deg; swl = +3.5 ft (with riverflow conditions)

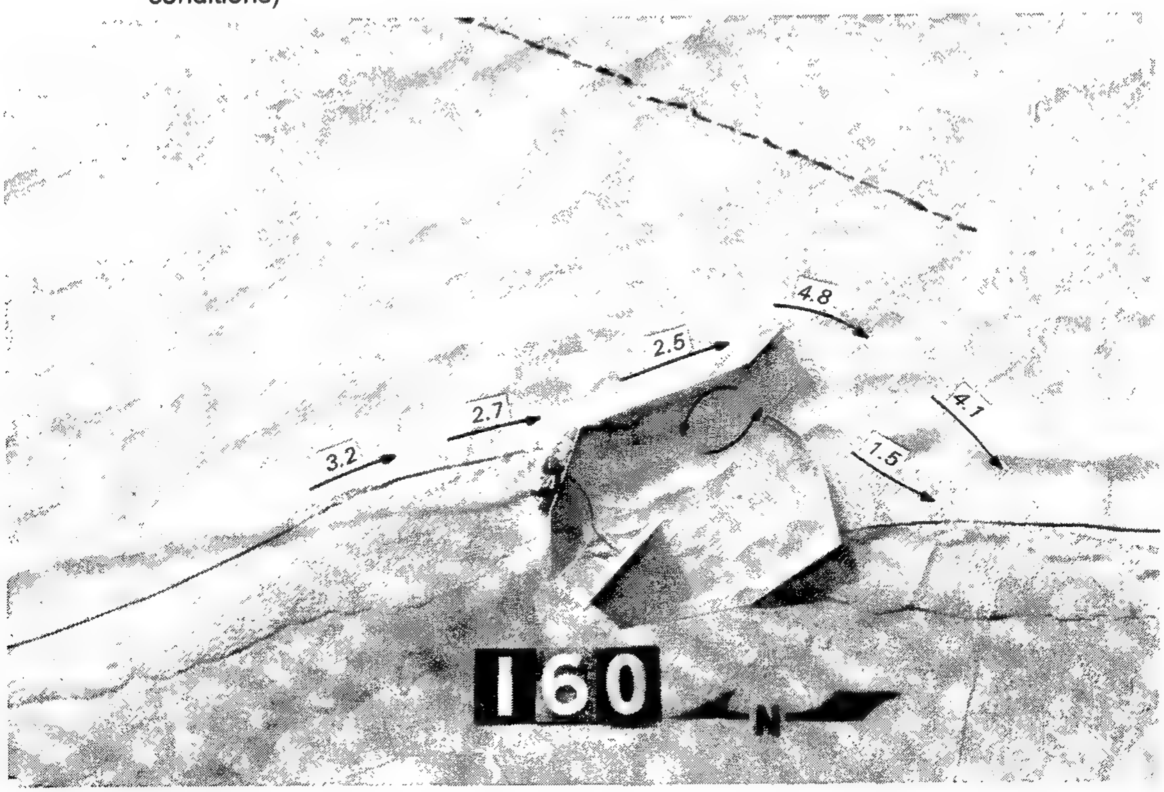



Photo 112. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 9; 6.5-sec, 7.7-ft waves from 59 deg; swl = +3.5 ft (with riverflow conditions)

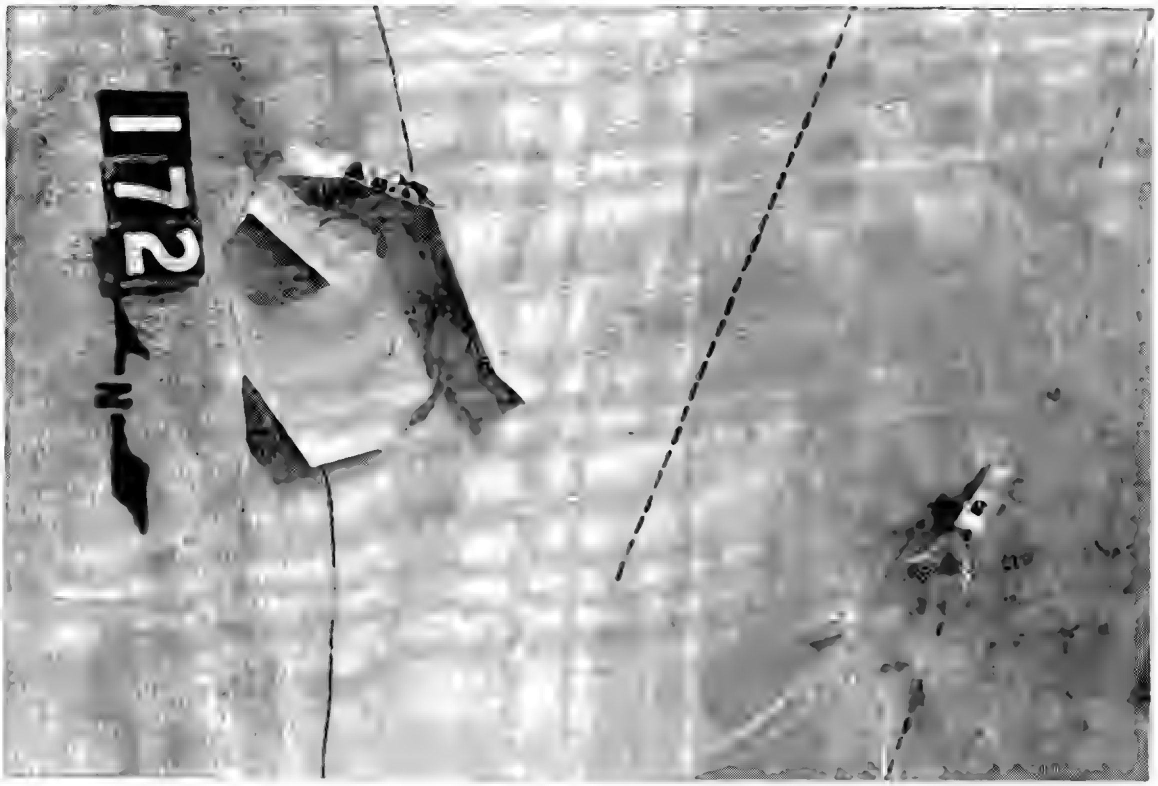



Photo 113. View of 27-m-long (90-ft-long) speedboat leaving St. Clair River for Plan 9

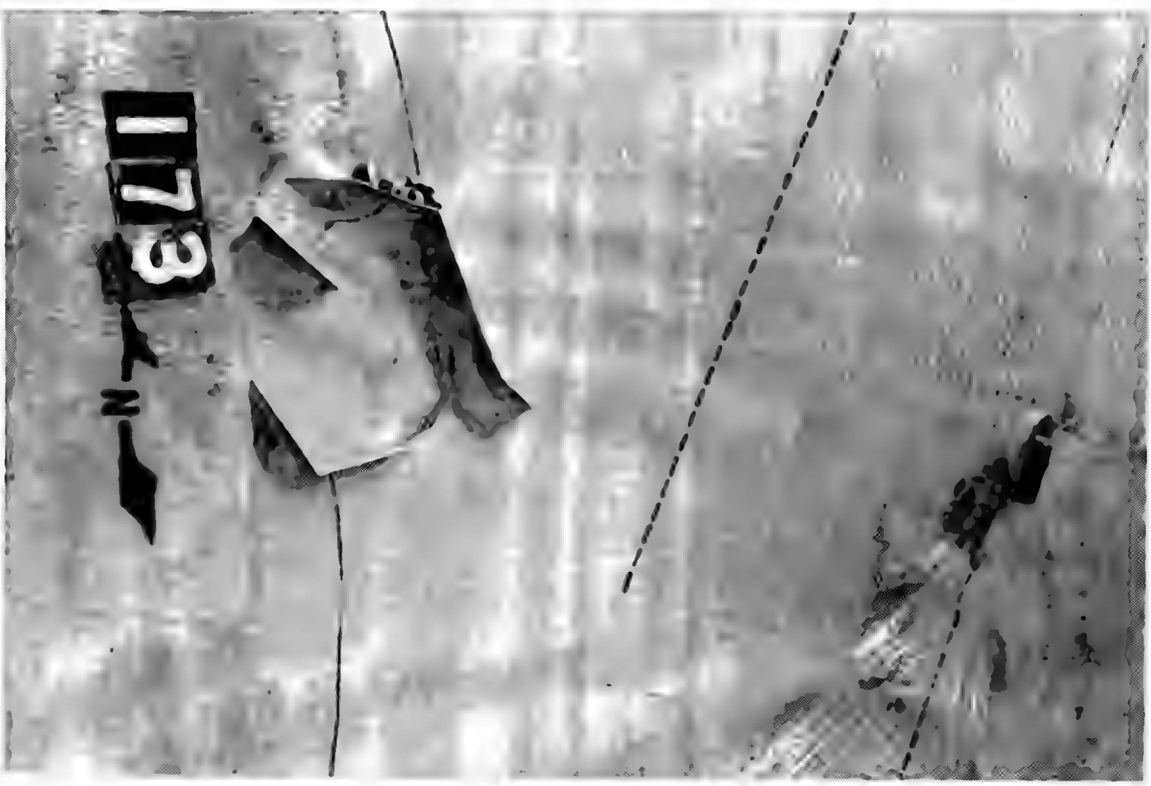



Photo 114. View of 30-m-long (100-ft-long) cabin cruiser leaving St. Clair River for Plan 9

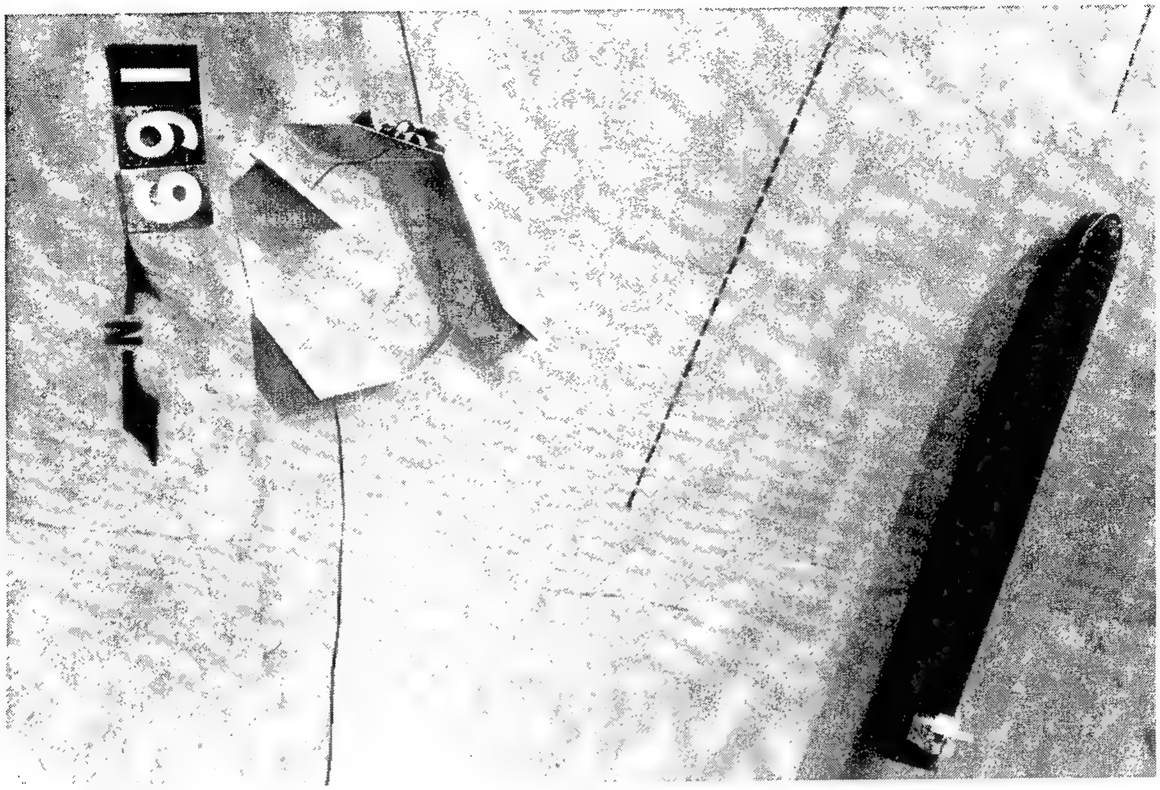



Photo 115. View of 183-m-long (600-ft-long) ore carrier leaving St. Clair River for Plan 9

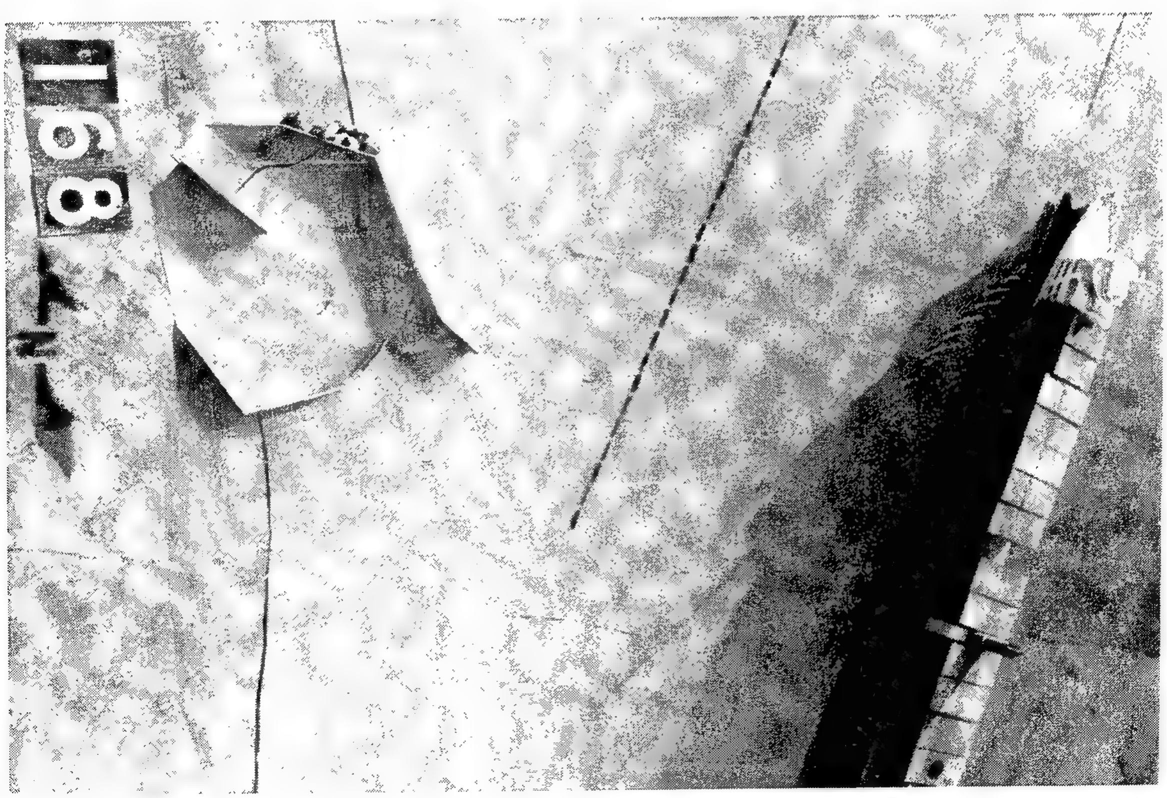



Photo 116. View of 210-m-long (690-ft-long) container vessel leaving St. Clair River for Plan 9

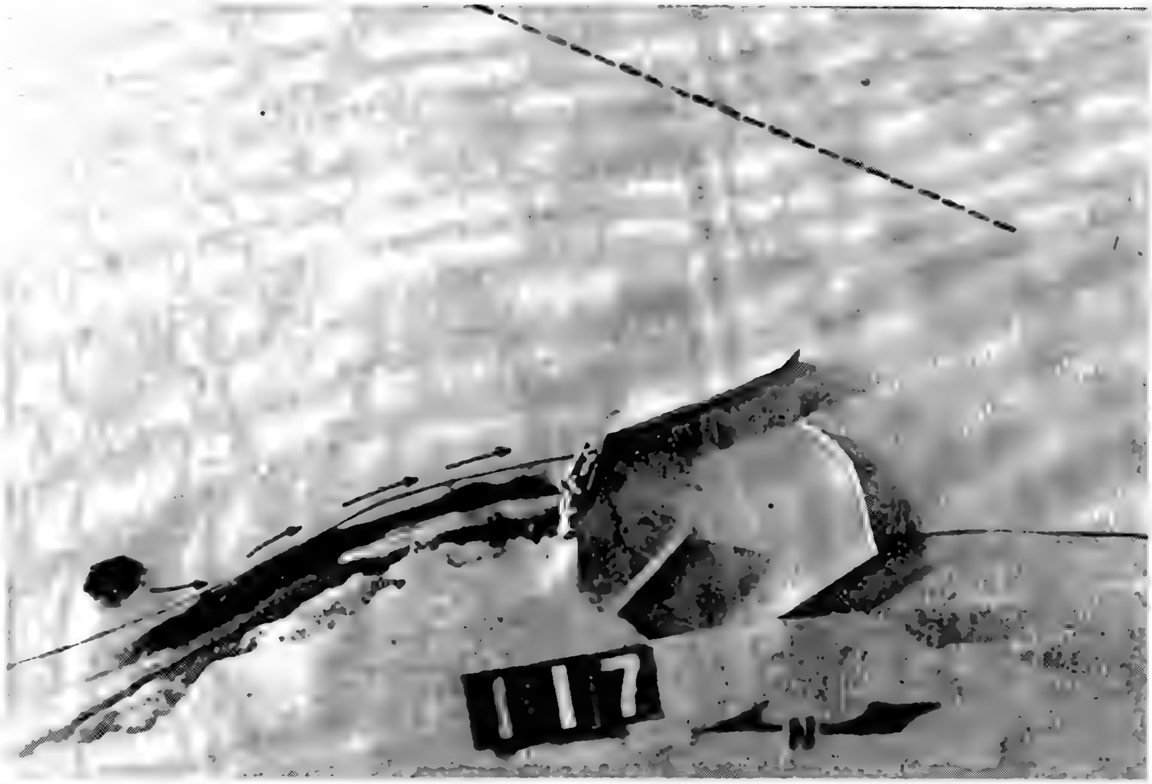



Photo 117. General movement of tracer material and subsequent deposits for Plan 10; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +1.7 ft (no riverflow conditions)

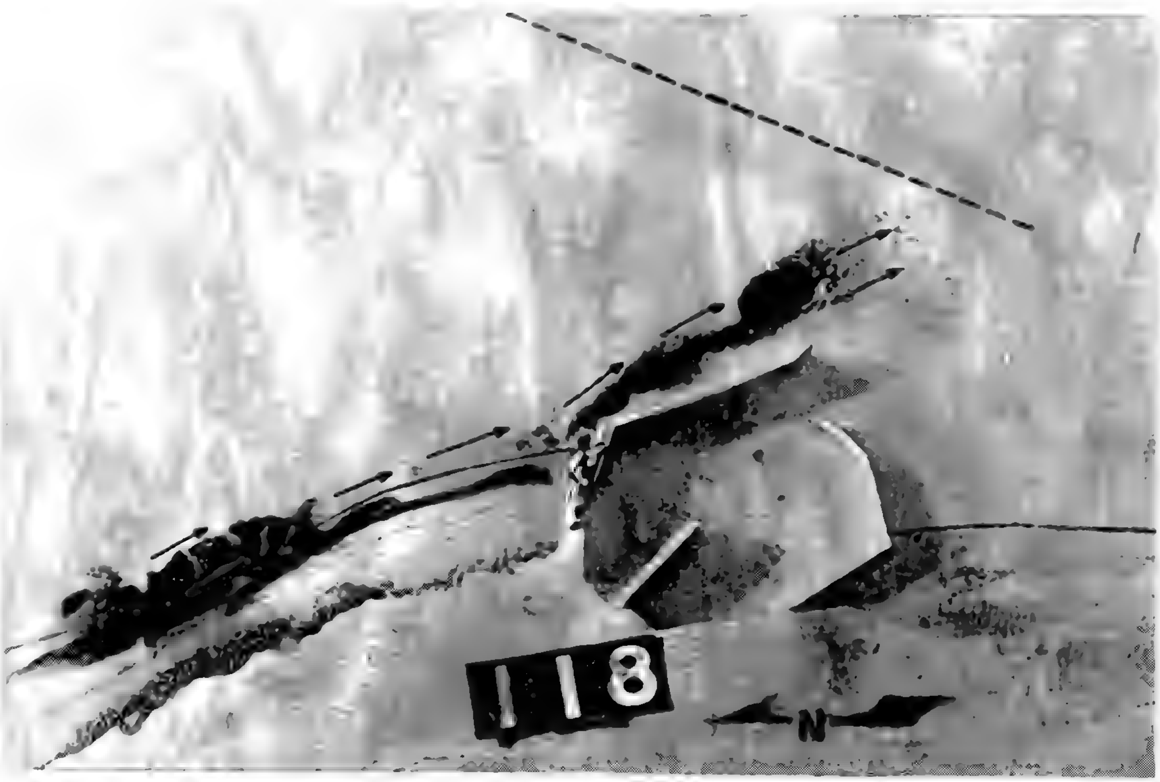



Photo 118. General movement of tracer material and subsequent deposits for Plan 10; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +1.7 ft (no riverflow conditions)

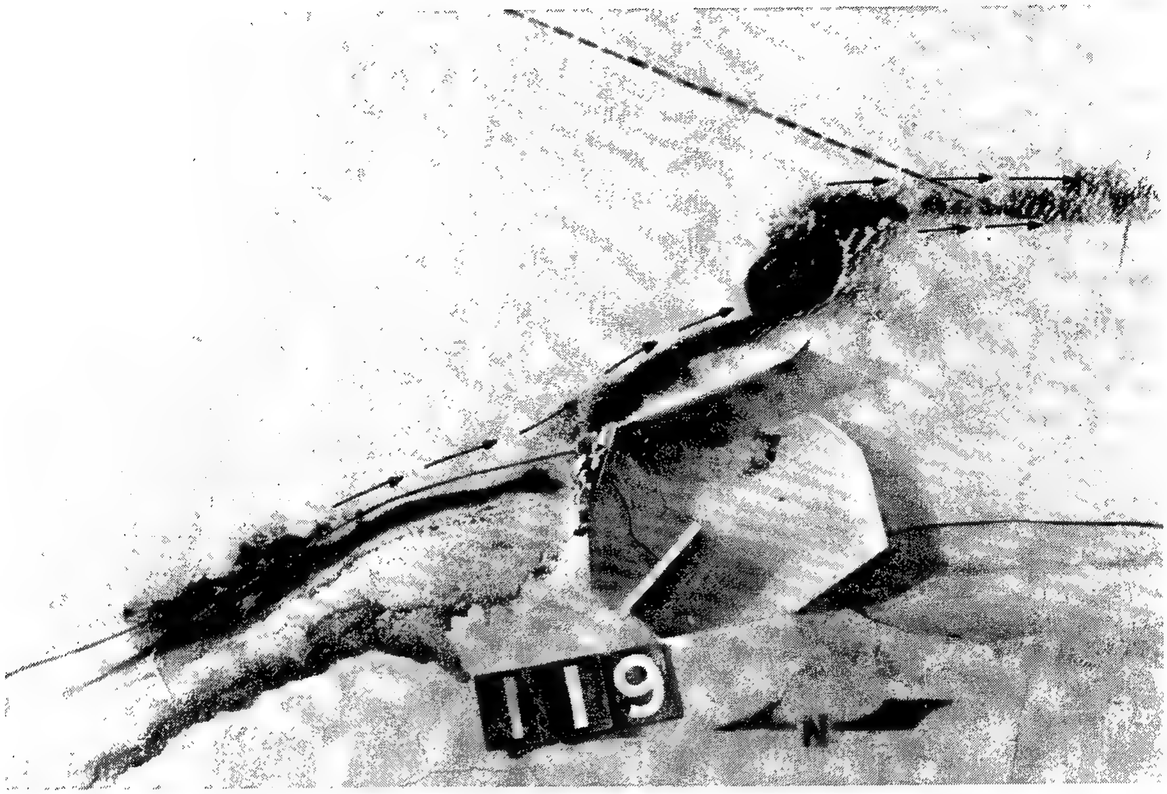



Photo 119. General movement of tracer material and subsequent deposits for Plan 10; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +1.7 ft (no riverflow conditions)

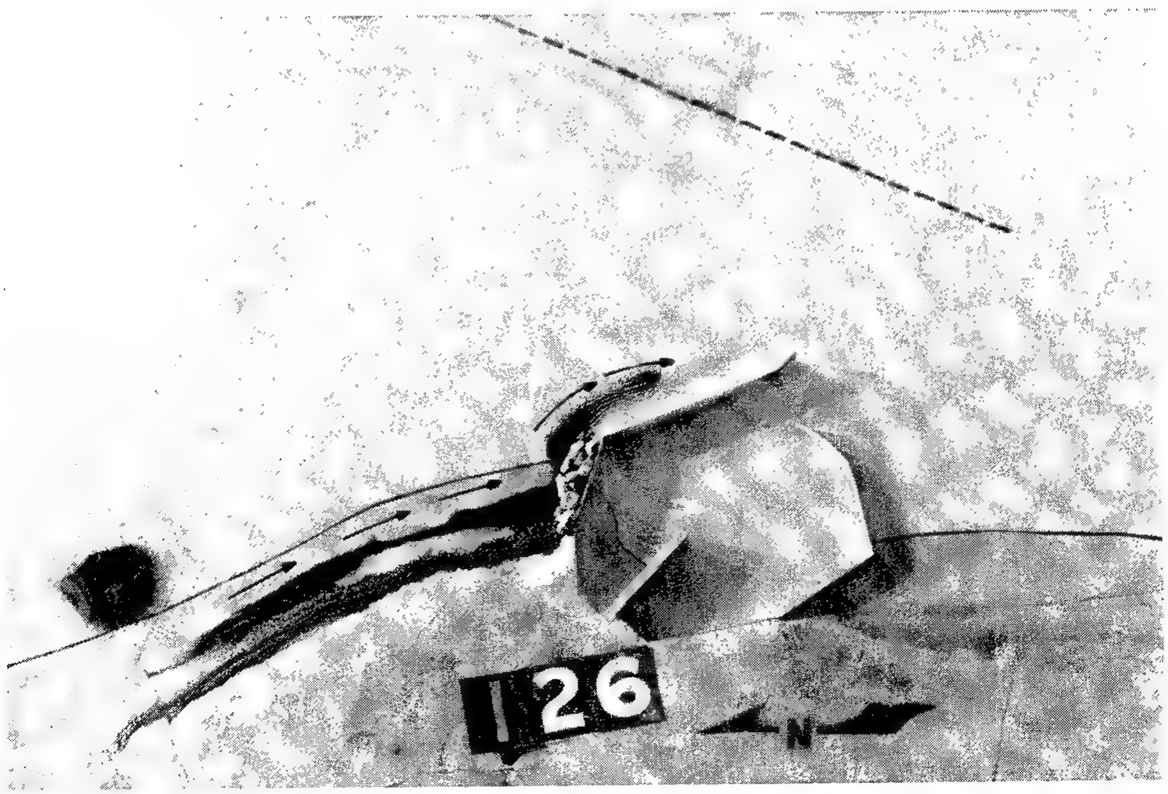



Photo 120. General movement of tracer material and subsequent deposits for Plan 10; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (no riverflow conditions)

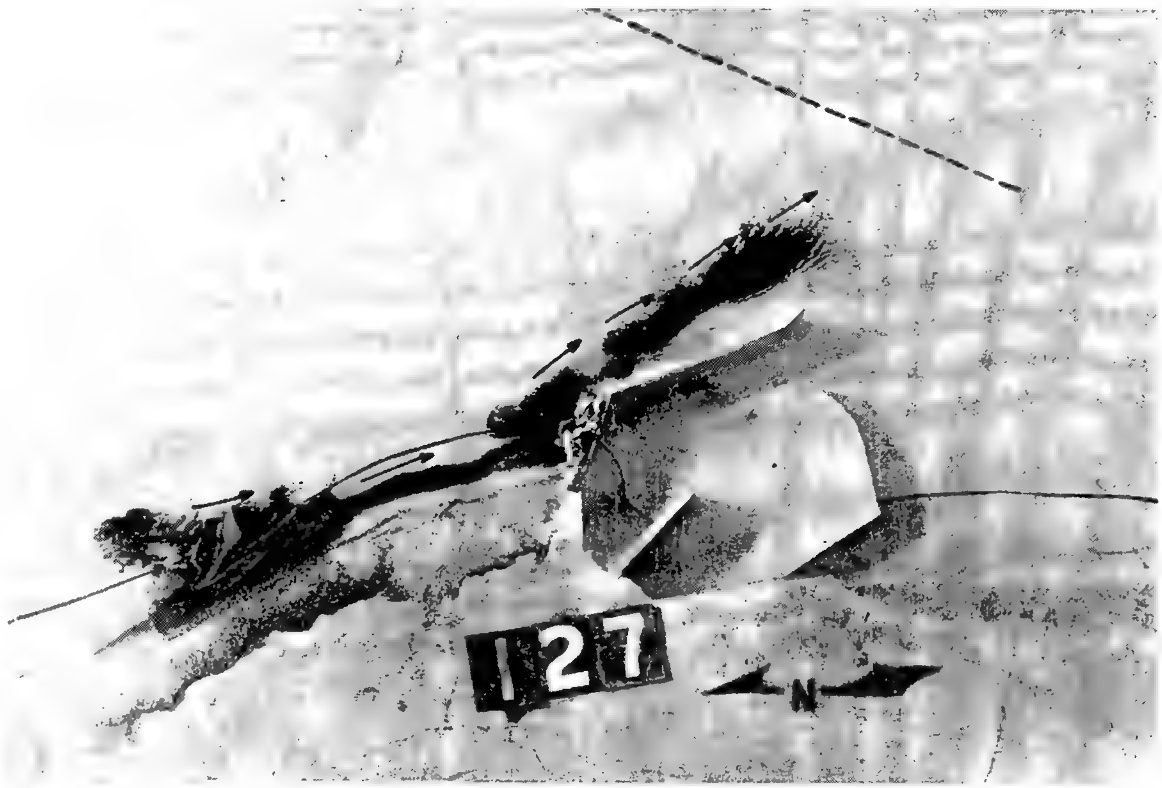



Photo 121. General movement of tracer material and subsequent deposits for Plan 10; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +3.5 ft (no riverflow conditions)

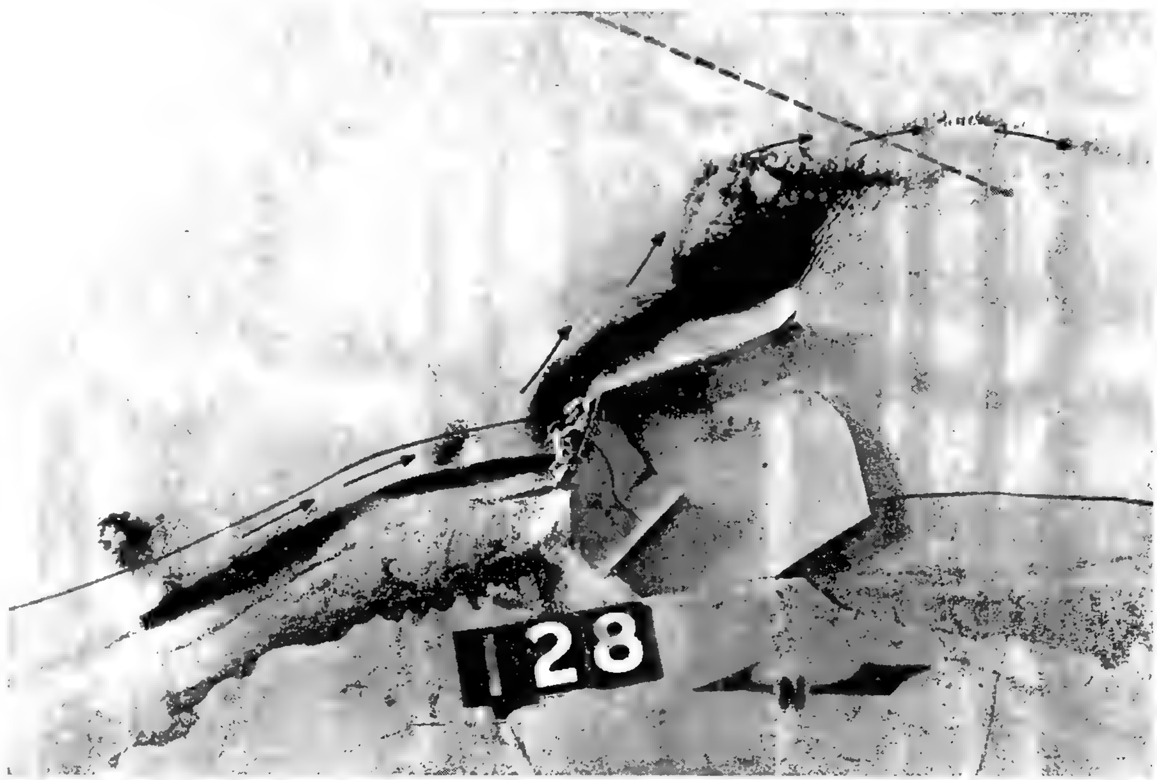



Photo 122. General movement of tracer material and subsequent deposits for Plan 10; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +3.5 ft (no riverflow conditions)

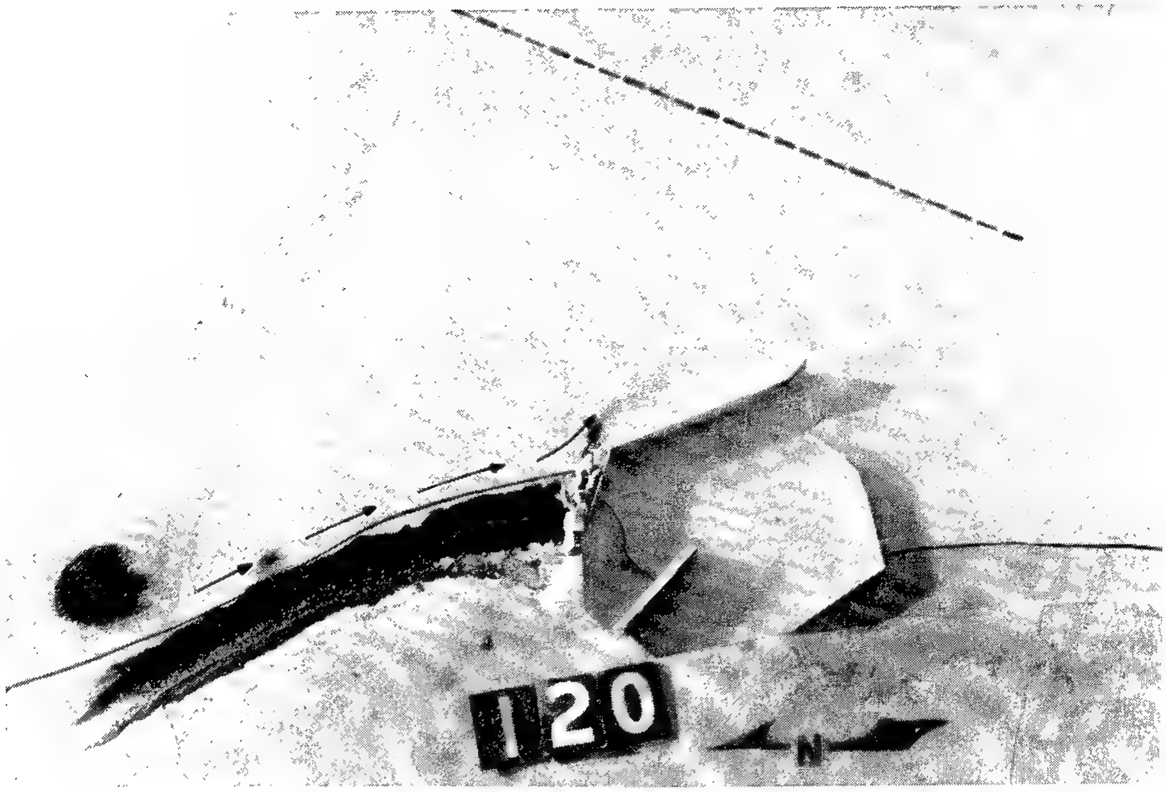



Photo 123. General movement of tracer material and subsequent deposits for Plan 10; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +1.7 ft (with riverflow conditions)

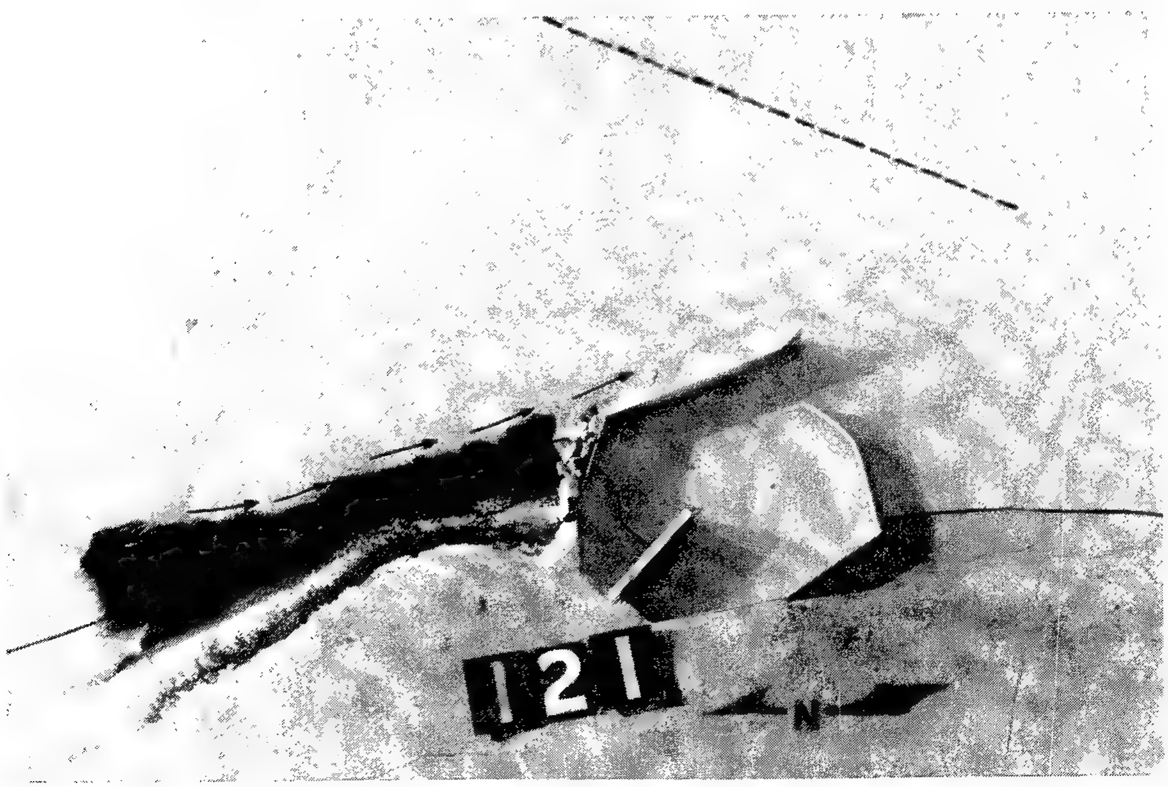



Photo 124. General movement of tracer material and subsequent deposits for Plan 10; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +1.7 ft (with riverflow conditions)

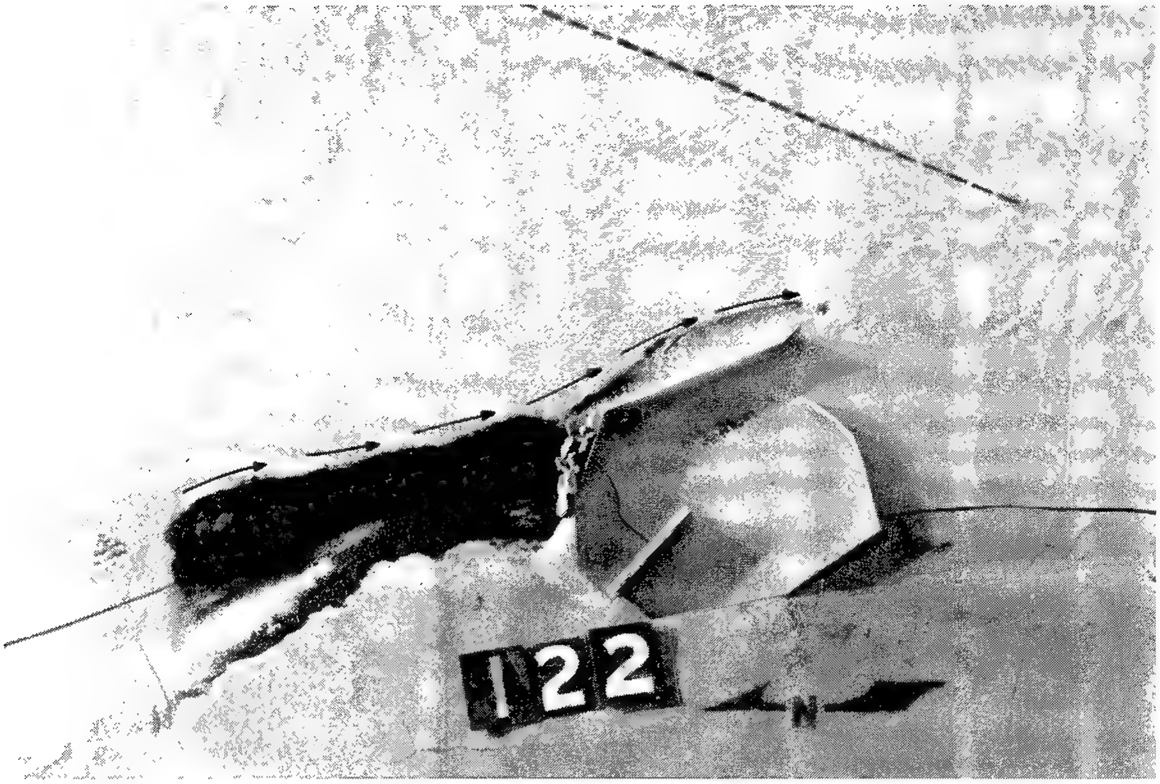



Photo 125. General movement of tracer material and subsequent deposits for Plan 10; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +1.7 ft (with riverflow conditions)

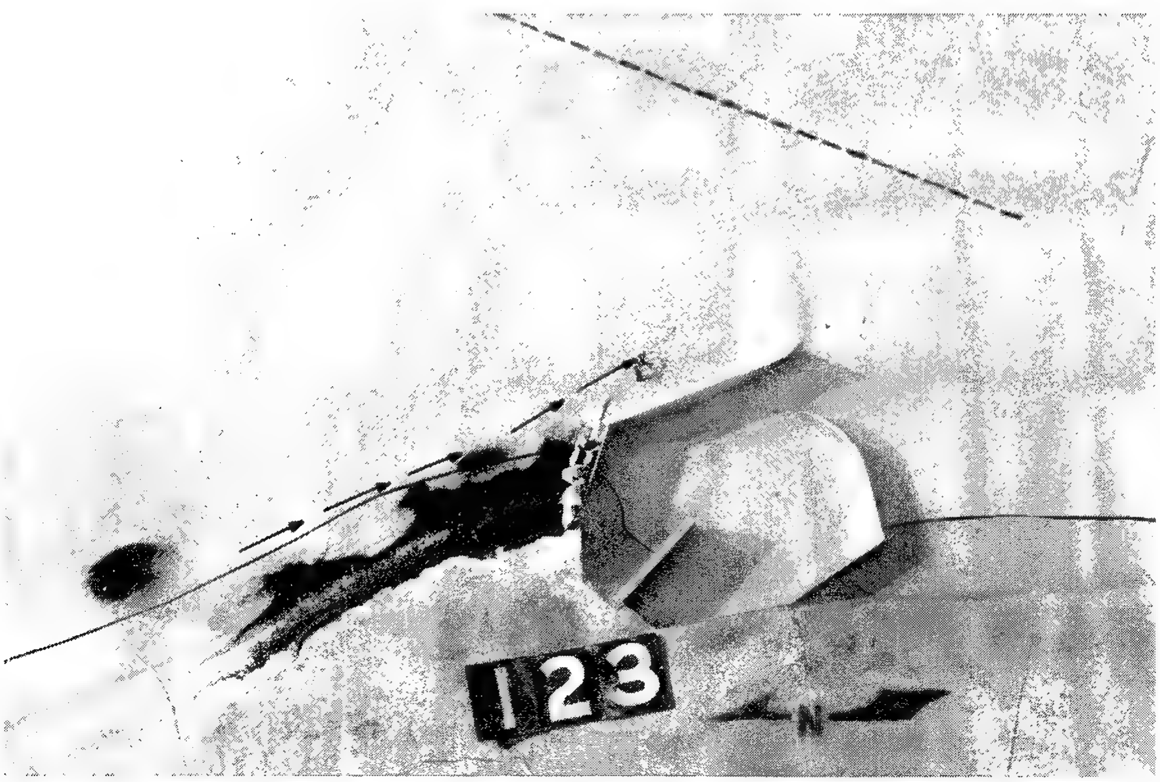



Photo 126. General movement of tracer material and subsequent deposits for Plan 10; 6.0-sec, 4.0-ft waves run for 40 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

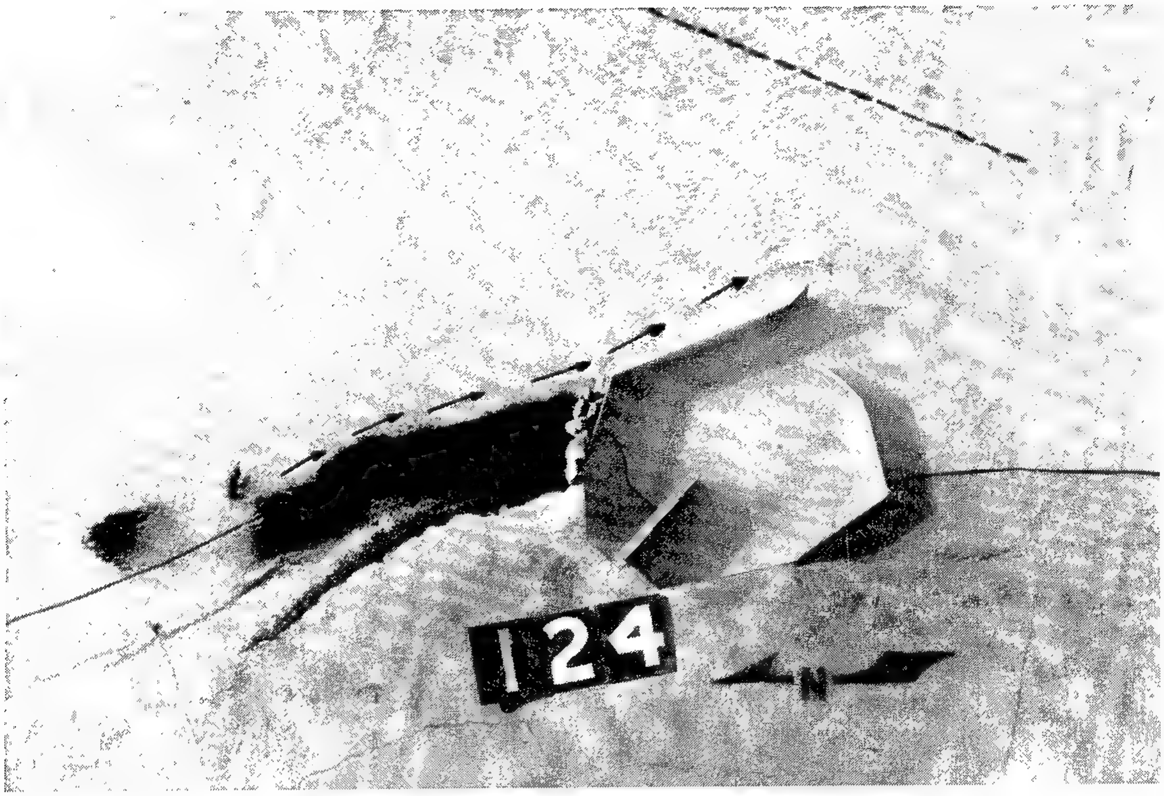



Photo 127. General movement of tracer material and subsequent deposits for Plan 10; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 5 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

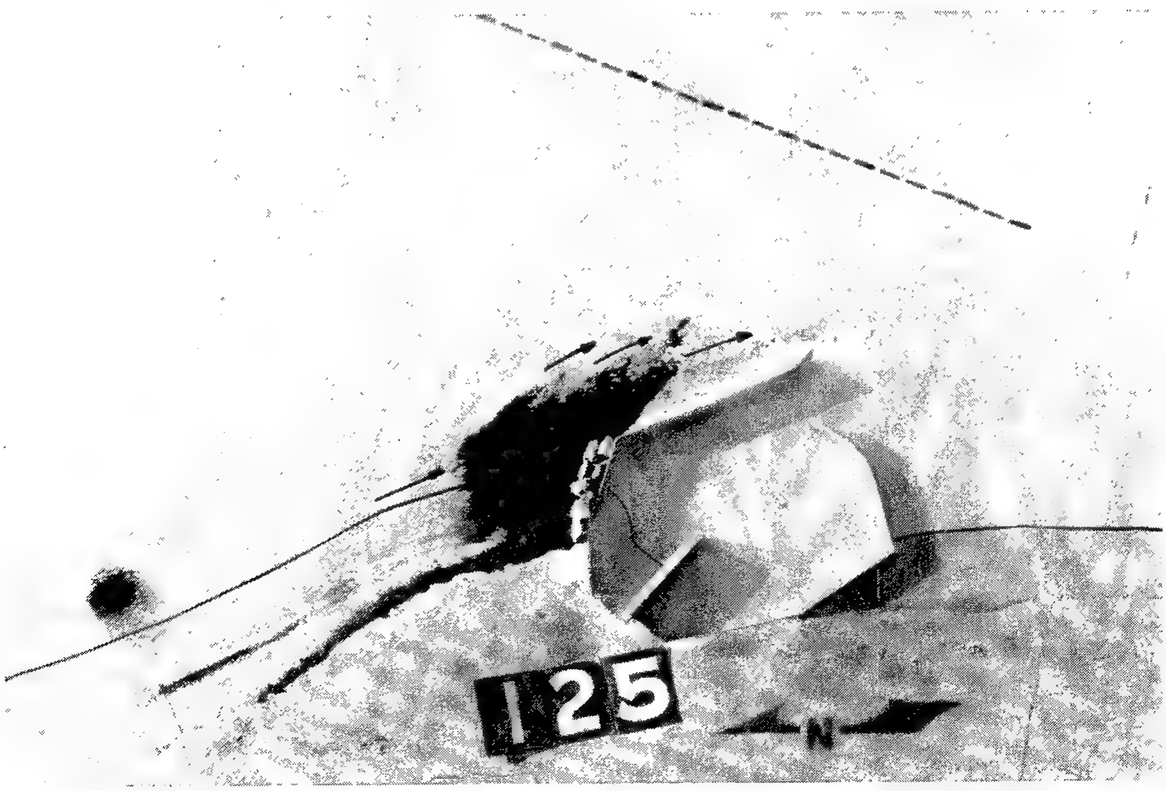



Photo 128. General movement of tracer material and subsequent deposits for Plan 10; 6.0-sec, 4.0-ft waves run for 40 min, and 7.9-sec, 6.8-ft waves run for 20 min from 11 deg; swl = +3.5 ft (with riverflow conditions)

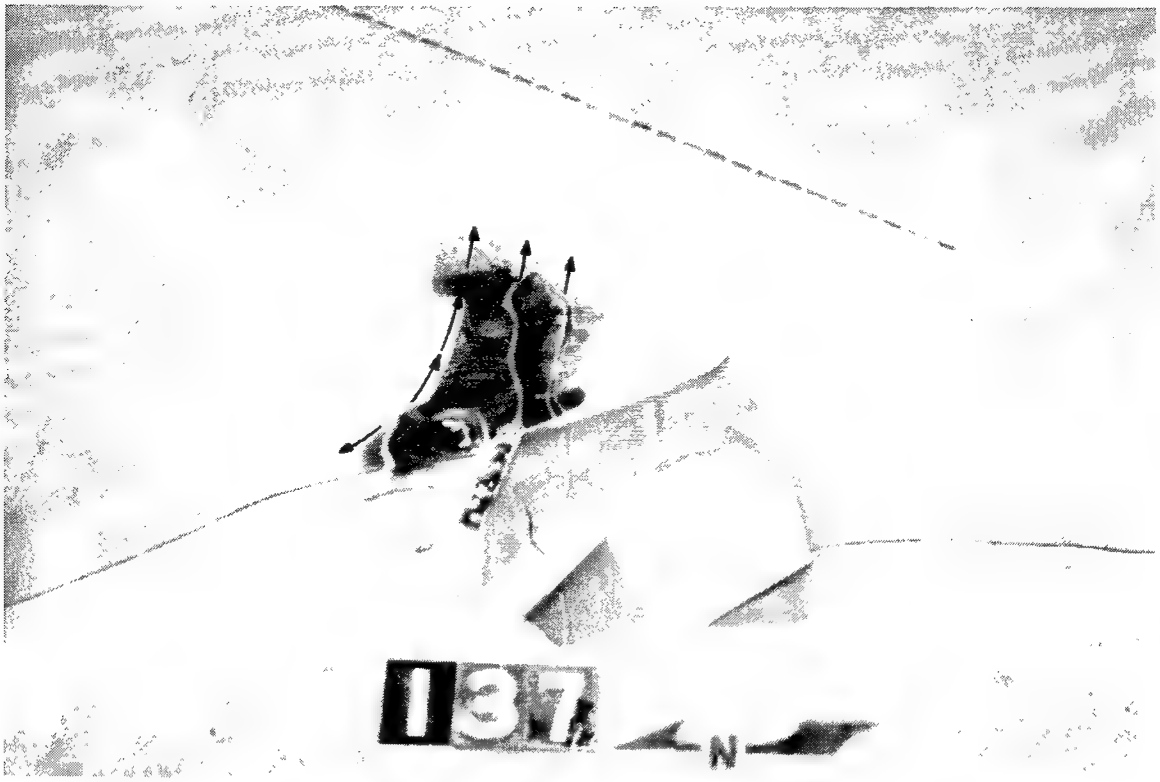



Photo 129. General movement of tracer material and subsequent deposits for Plan 10; 5.0-sec, 4.0-ft waves run for 10 min from 59 deg; swl = +1.7 ft (no riverflow conditions)

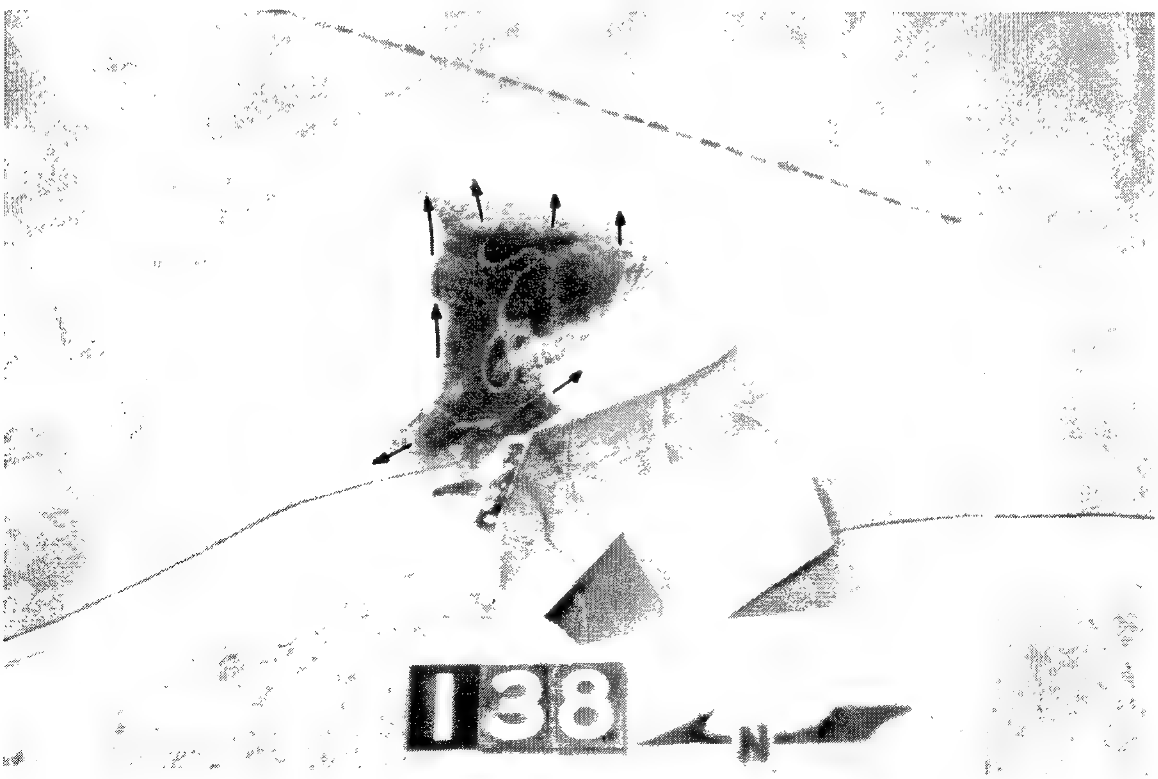



Photo 130. General movement of tracer material and subsequent deposits for Plan 10; 5.0-sec, 4.0-ft waves run for 10 min, and 6.0-sec, 6.1-ft waves run for 5 min from 59 deg; swl = +1.7 ft (no riverflow conditions)

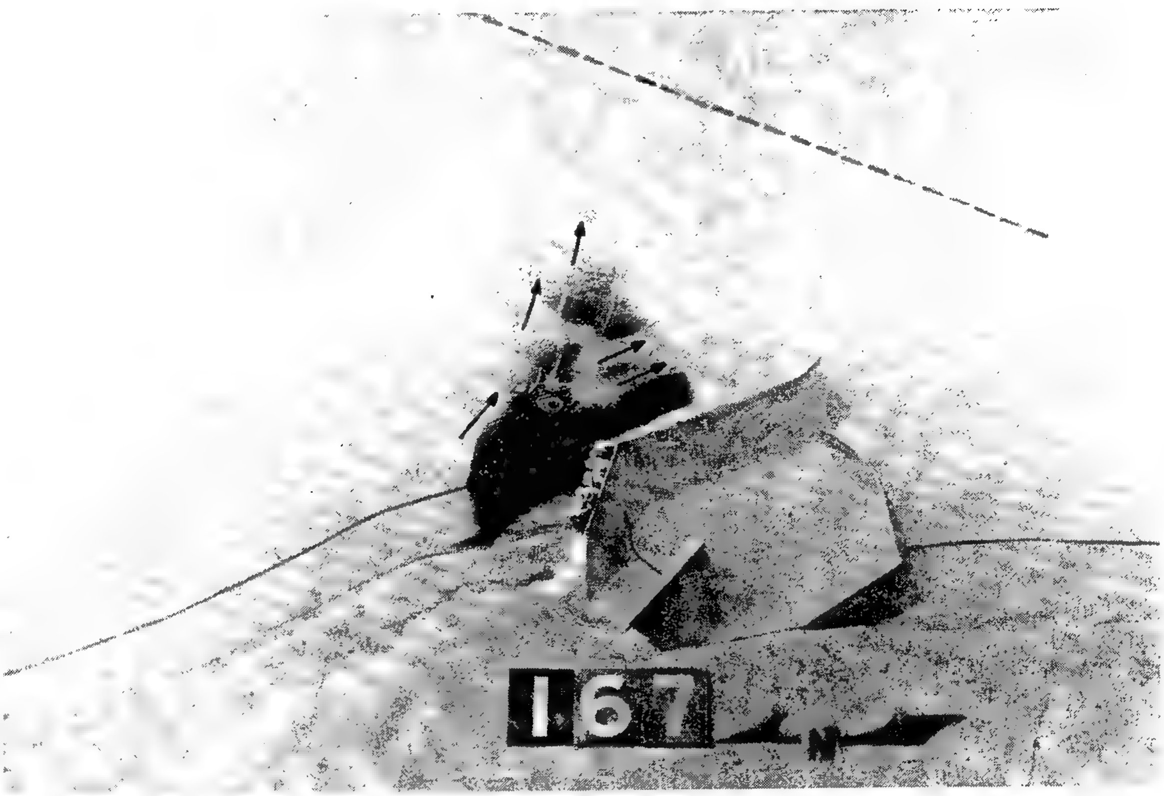



Photo 131. General movement of tracer material and subsequent deposits for Plan 10; 5.0-sec, 4.0-ft waves run for 10 min from 59 deg; swl = +3.5 ft (no riverflow conditions)

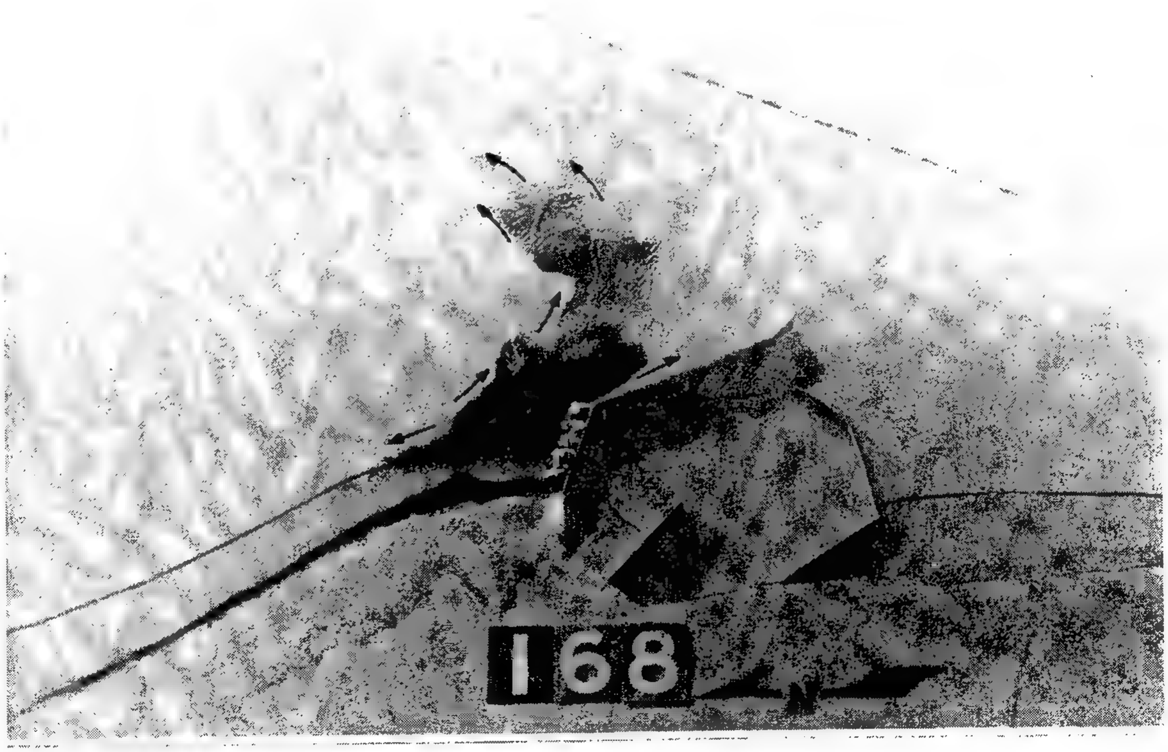



Photo 132. General movement of tracer material and subsequent deposits for Plan 10; 5.0-sec, 4.0-ft waves run for 10 min, and 6.0-sec, 6.1-ft waves run for 5 min from 59 deg; swl = +3.5 ft (no riverflow conditions)

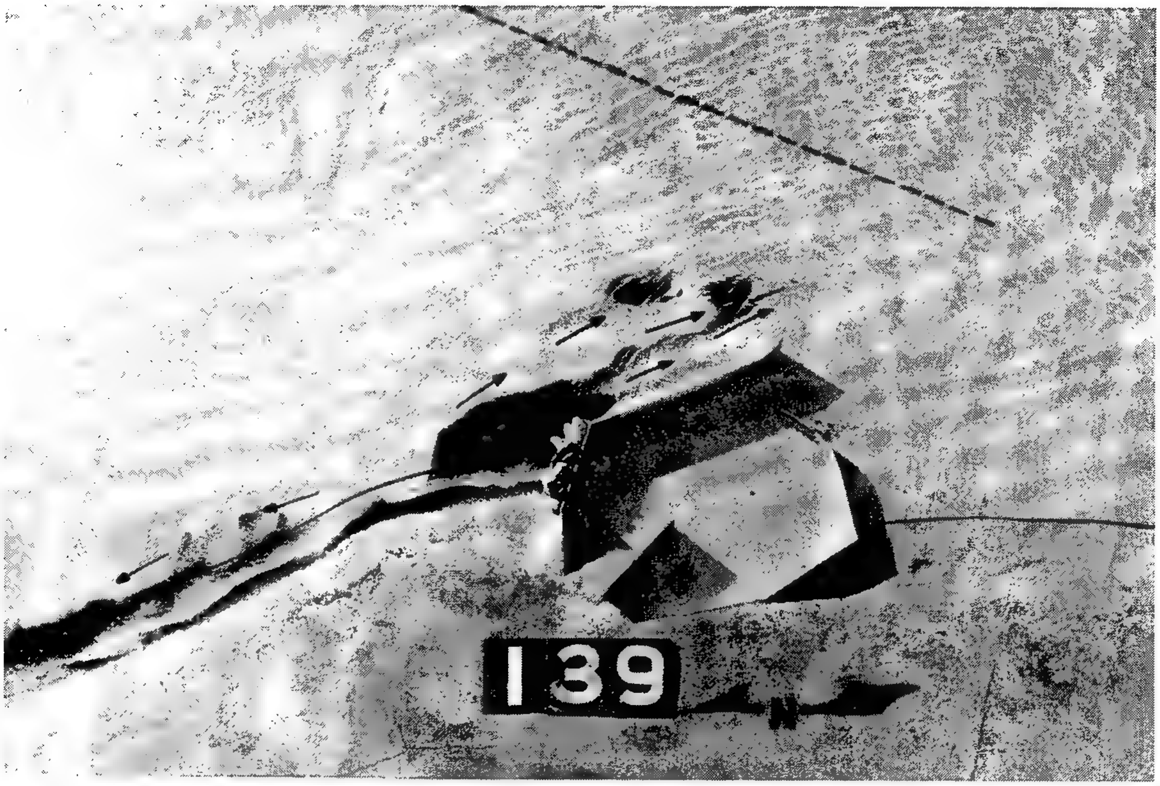



Photo 133. General movement of tracer material and subsequent deposits for Plan 10; 5.0-sec, 4.0-ft waves run for 10 min from 59 deg; swl = +1.7 ft (with riverflow conditions)

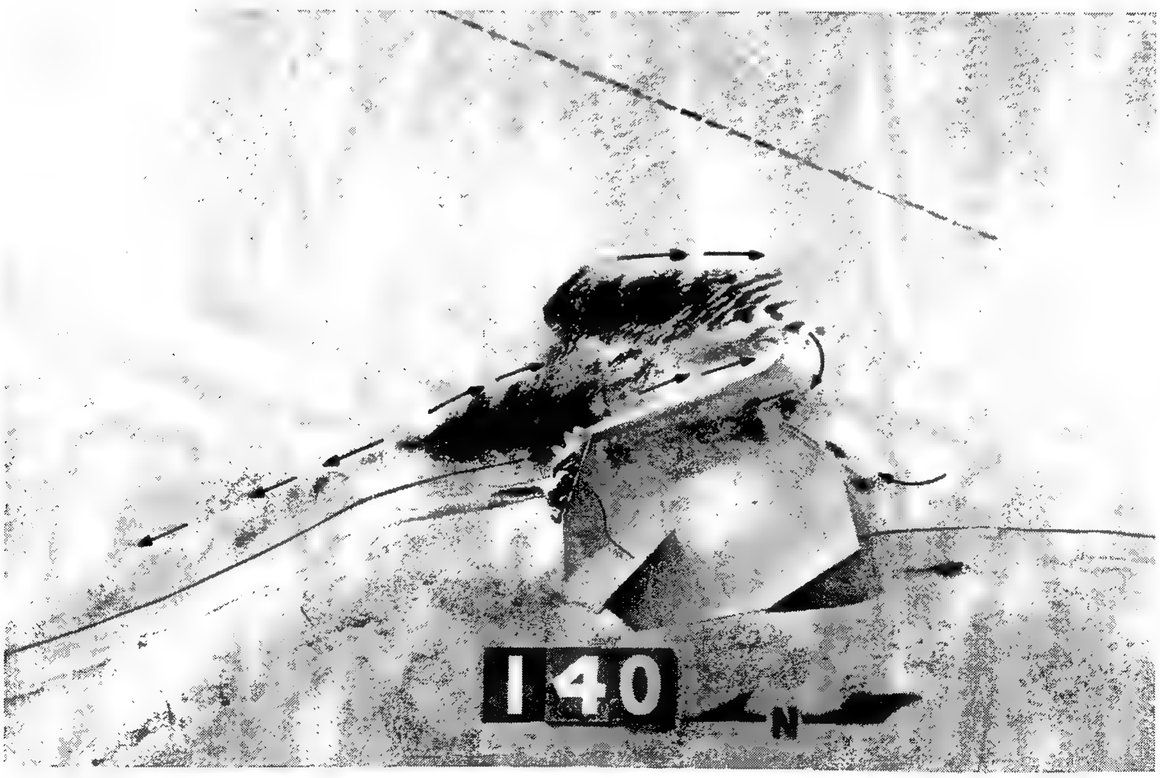



Photo 134. General movement of tracer material and subsequent deposits for Plan 10; 5.0-sec, 4.0-ft waves run for 10 min, and 6.0-sec, 6.1-ft waves run for 5 min from 59 deg; swl = +1.7 ft (with riverflow conditions)

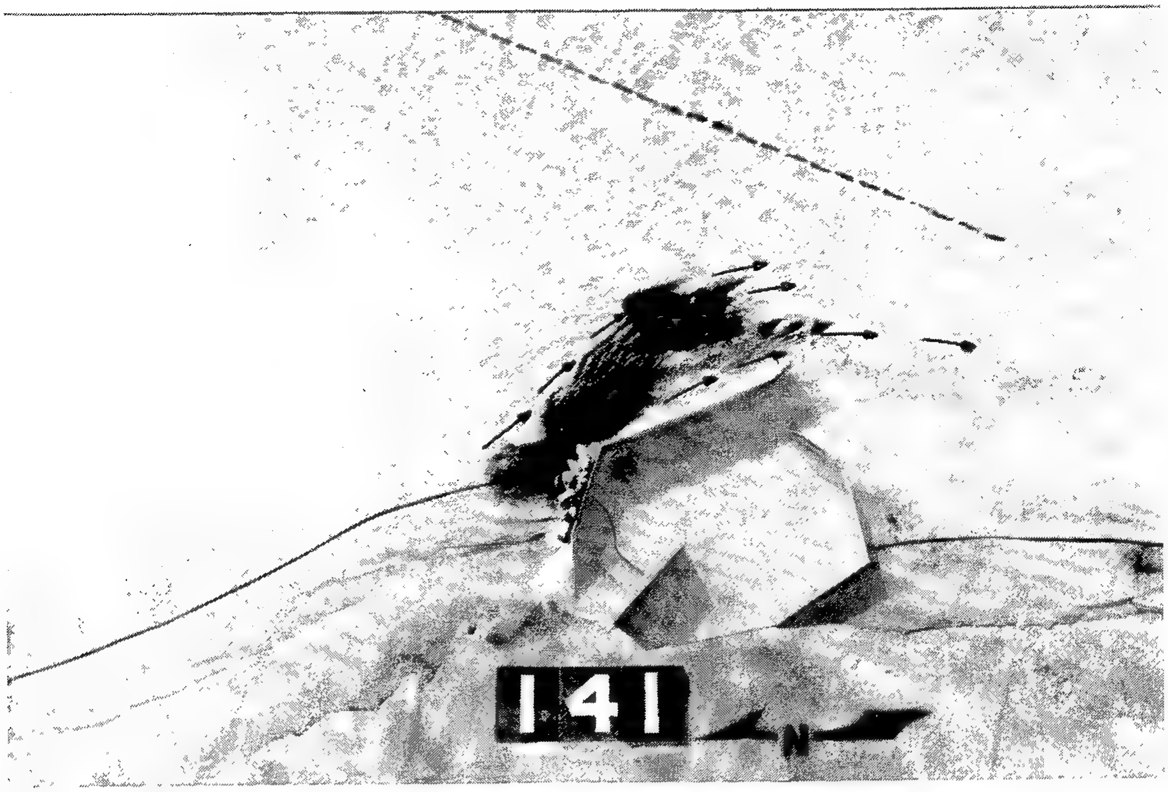



Photo 135. General movement of tracer material and subsequent deposits for Plan 10; 5.0-sec, 4.0-ft waves run for 10 min from 59 deg; swl = +3.5 ft (with riverflow conditions)

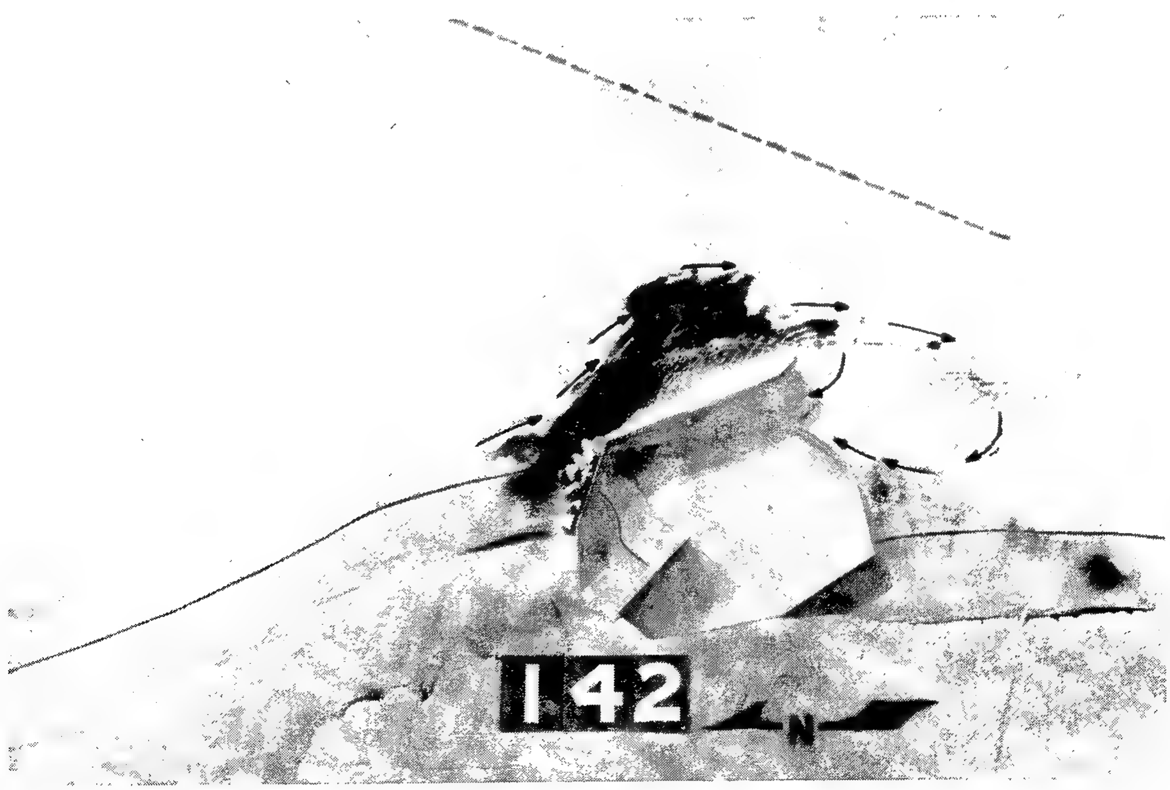



Photo 136. General movement of tracer material and subsequent deposits for Plan 10; 5.0-sec, 4.0-ft waves run for 10 min, and 6.0-sec, 6.1-ft waves run for 5 min from 59 deg; swl = +3.5 ft (with riverflow conditions)

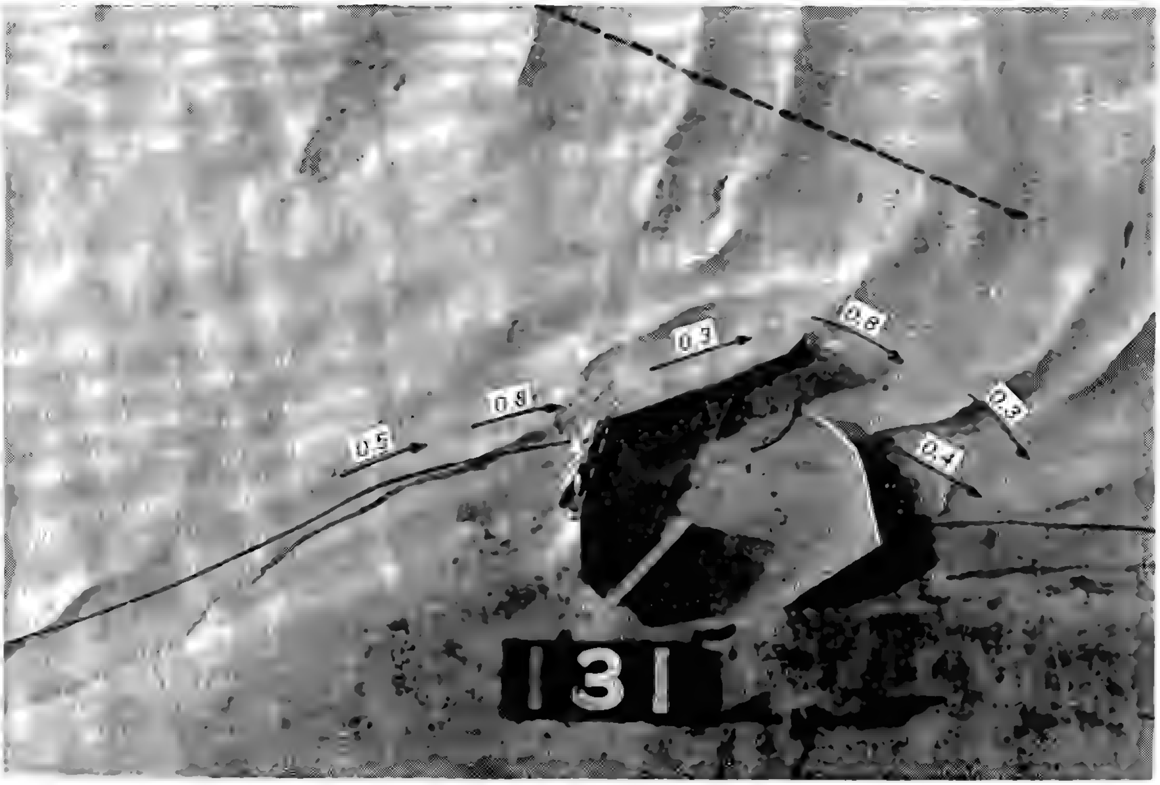



Photo 137. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 6.0-sec, 4.0-ft waves from 11 deg; swl = +1.7 ft (no riverflow conditions)

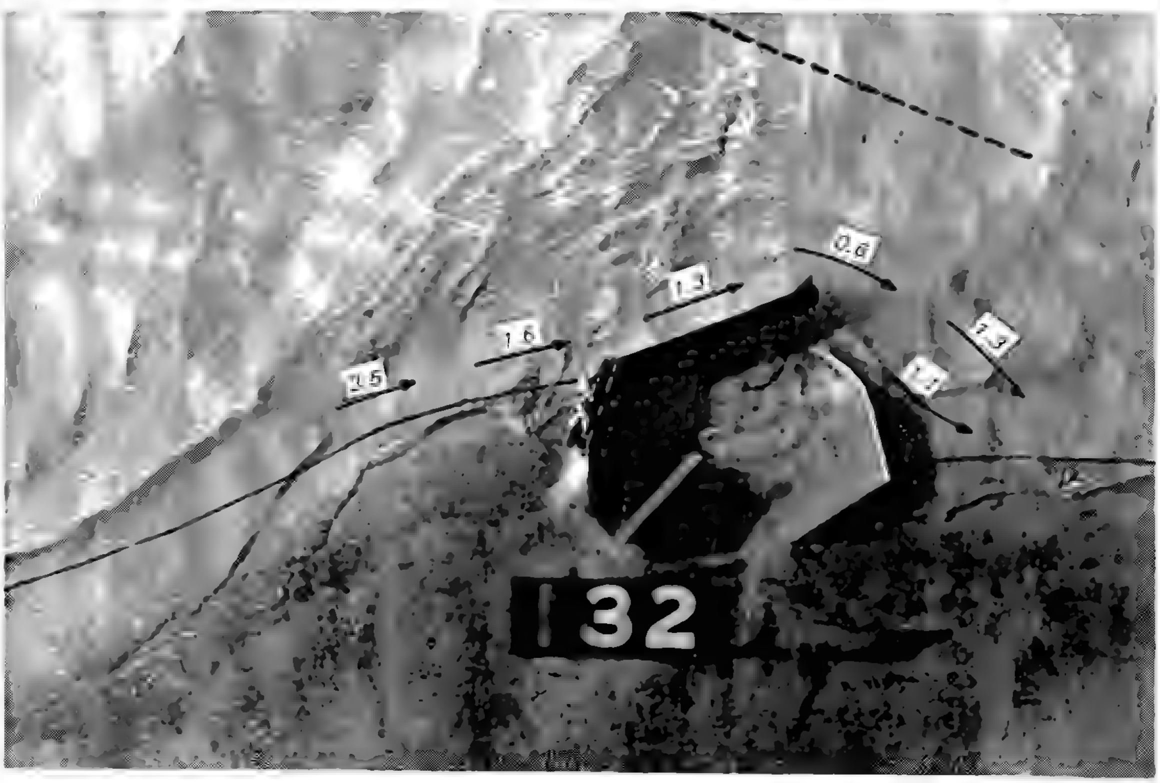



Photo 138. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 8.6-sec, 8.6-ft waves from 11 deg; swl = +1.7 ft (no riverflow conditions)

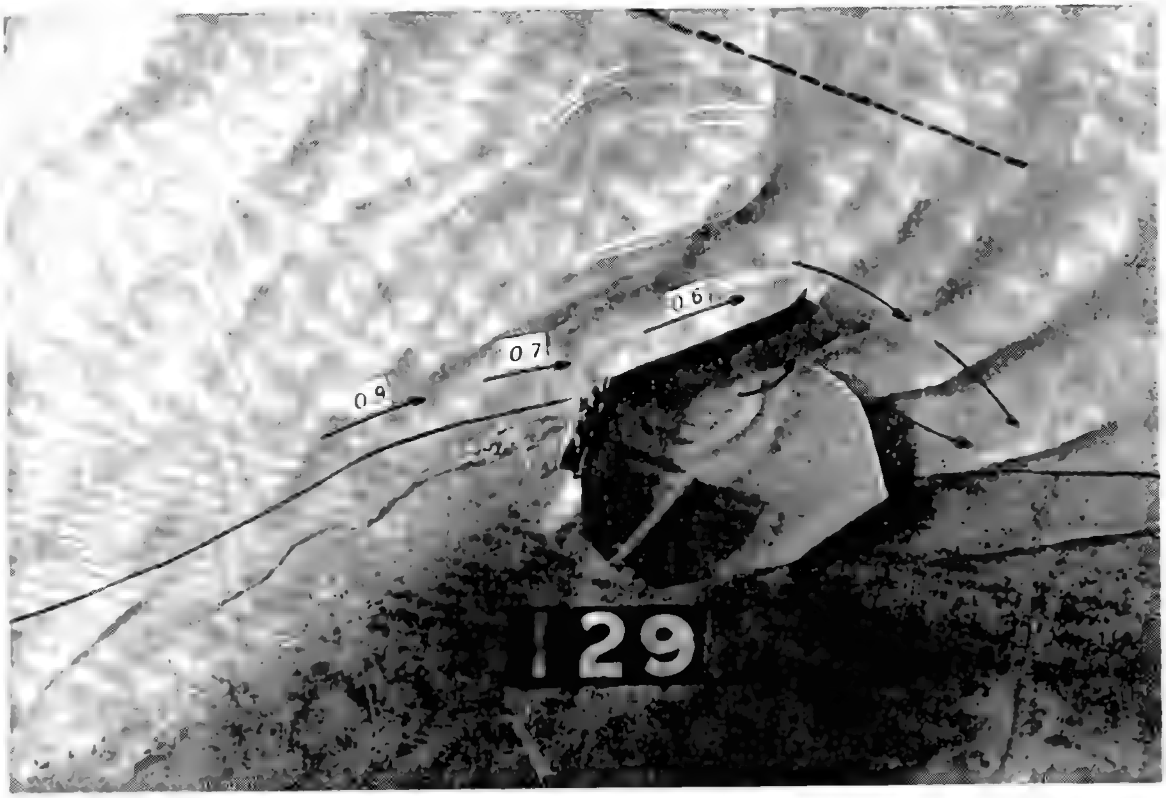



Photo 139. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 6.0-sec, 4.0-ft waves from 11 deg; swl = +3.5 ft (no riverflow conditions)

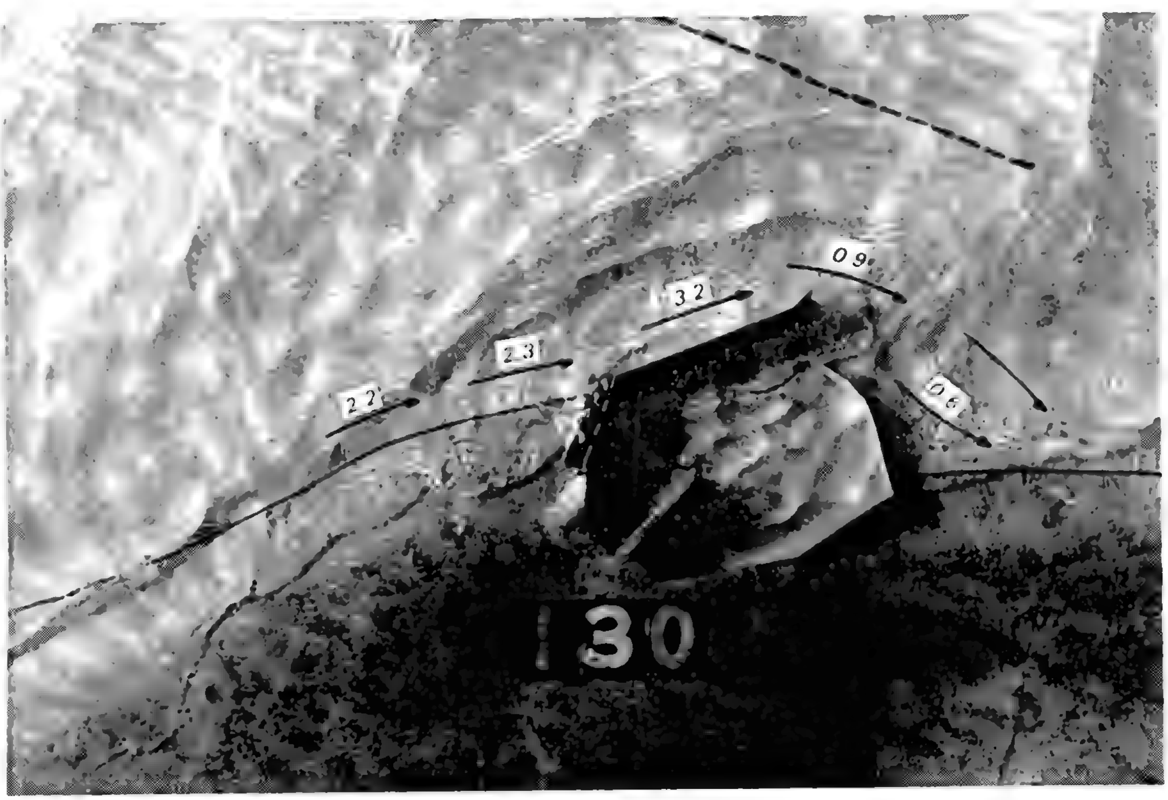



Photo 140. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 8.6-sec, 8.6-ft waves from 11 deg; swl = +3.5 ft (no riverflow conditions)

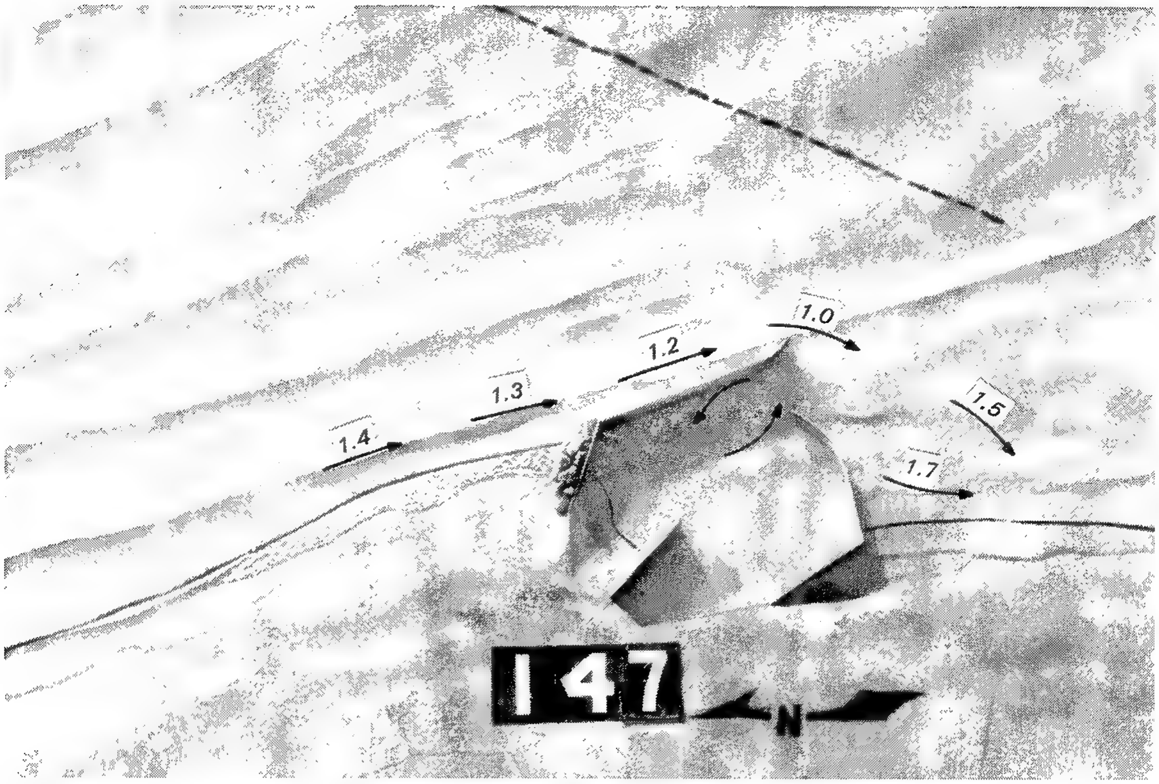



Photo 141. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 5.0-sec, 4.0-ft waves from 59 deg; swl = +1.7 ft (no riverflow conditions)

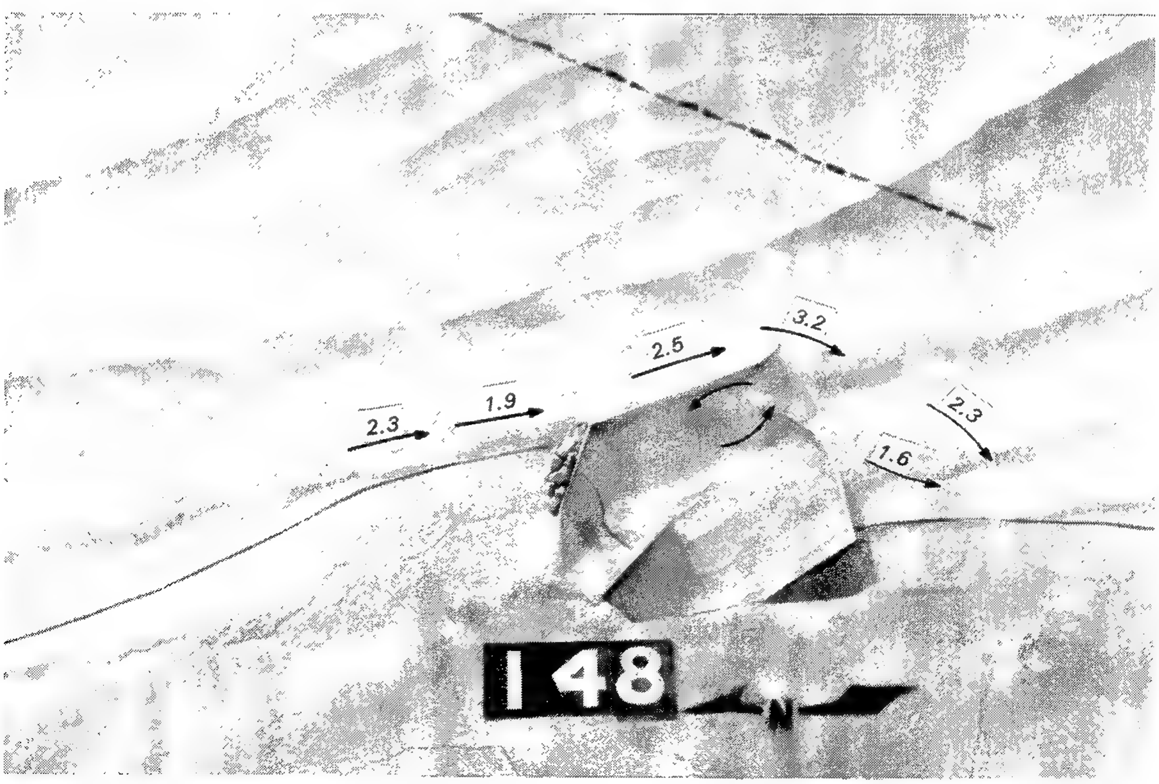



Photo 142. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 6.5-sec, 7.7-ft waves from 59 deg; swl = +1.7 ft (no riverflow conditions)

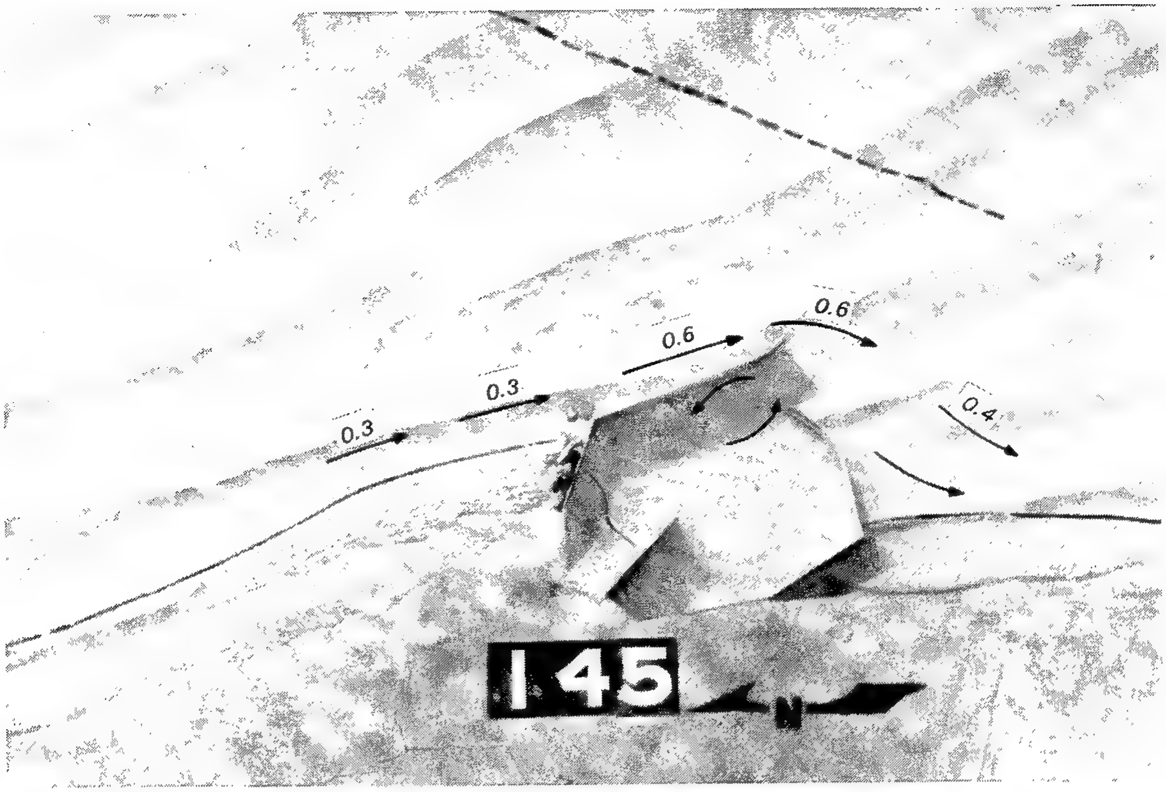



Photo 143. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 5.0-sec, 4.0-ft waves from 59 deg; swl = +3.5 ft (no riverflow conditions)

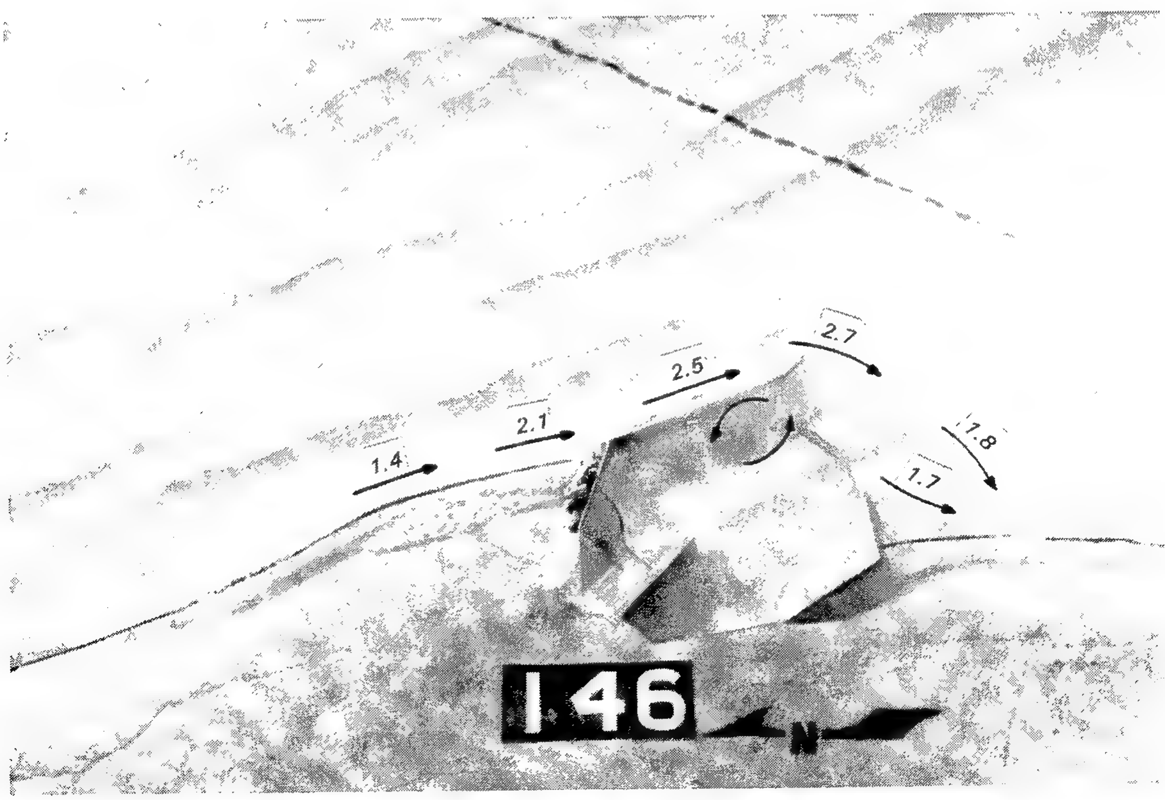



Photo 144. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 6.5-sec, 7.7-ft waves from 59 deg; swl = +3.5 ft (no riverflow conditions)

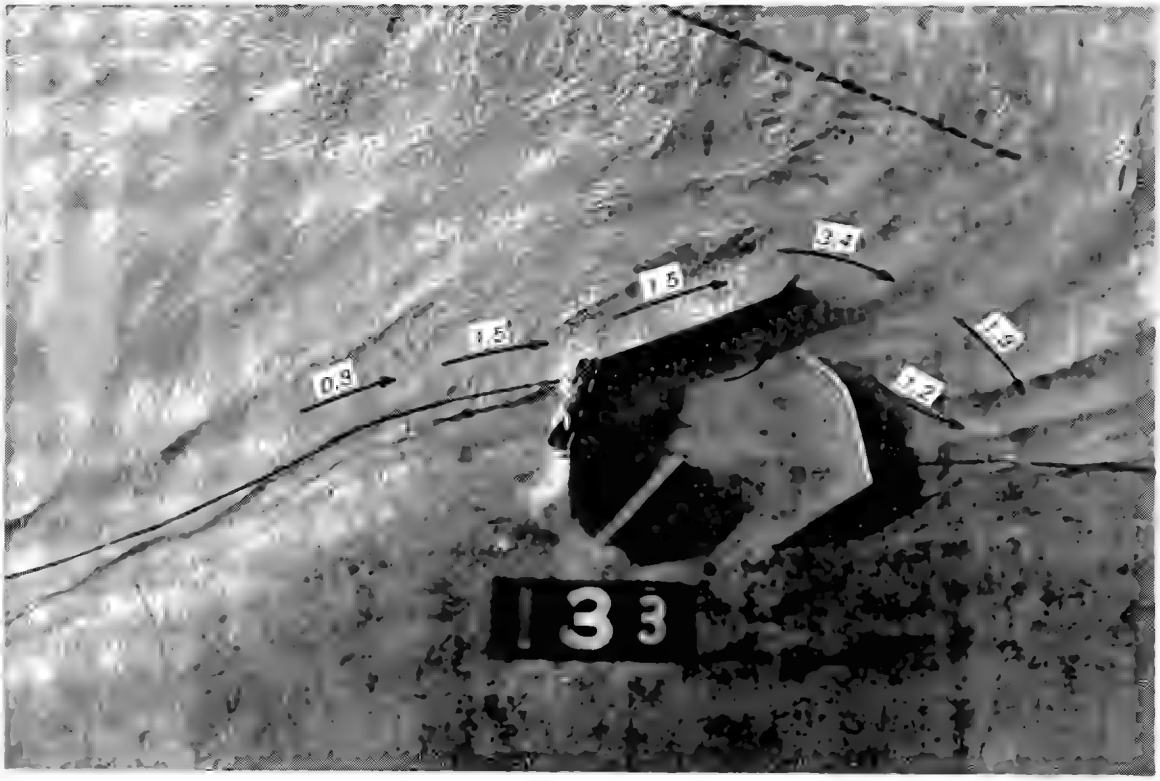



Photo 145. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 6.0-sec, 4.0-ft waves from 11 deg; swl = +1.7 ft (with riverflow conditions)

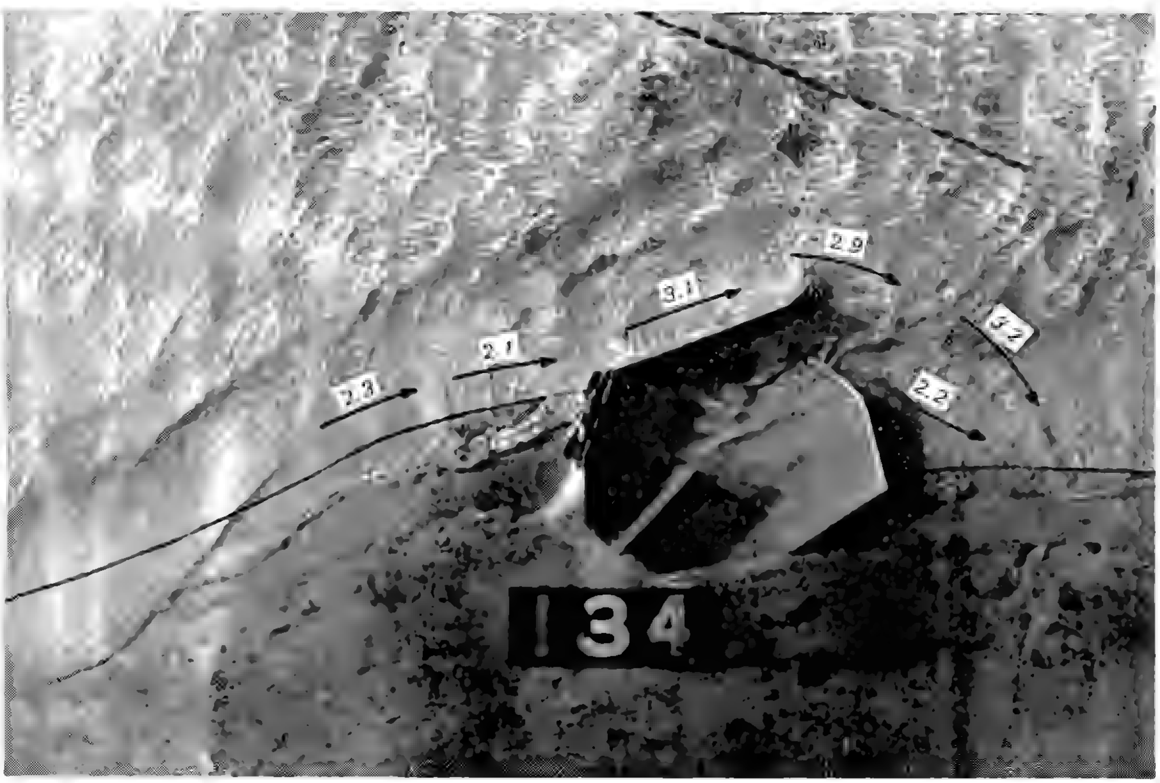



Photo 146. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 8.6-sec, 8.6-ft waves from 11 deg; swl = +1.7 ft (with riverflow conditions)

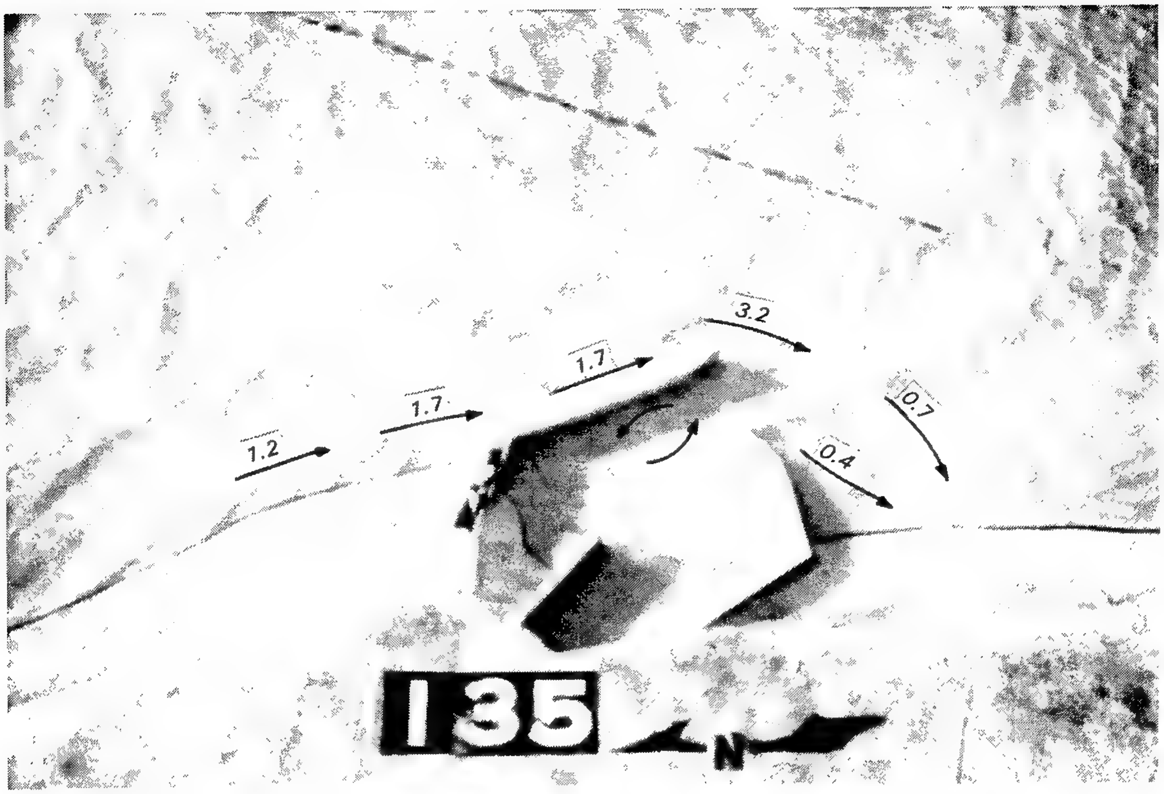



Photo 147. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 6.0-sec, 4.0-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

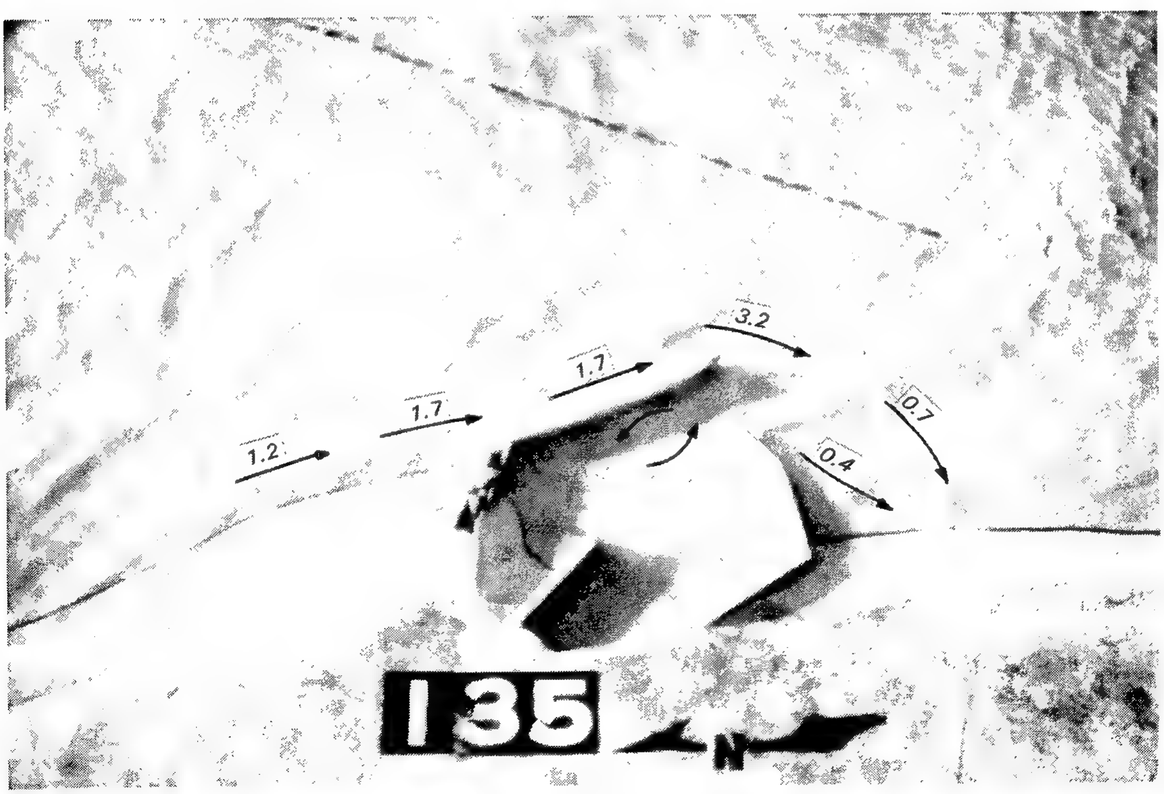



Photo 148. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 8.6-sec, 8.6-ft waves from 11 deg; swl = +3.5 ft (with riverflow conditions)

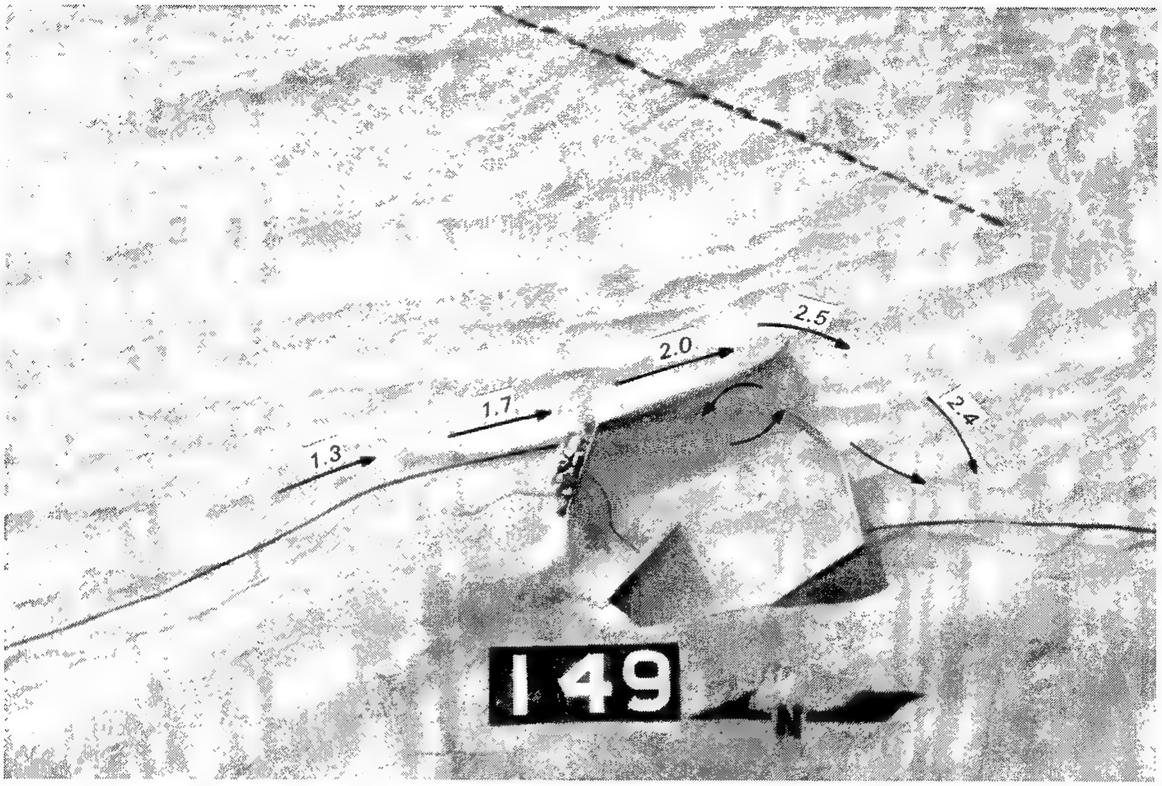



Photo 149. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 5.0-sec, 4.0-ft waves from 59 deg; swl = +1.7 ft (with riverflow conditions)

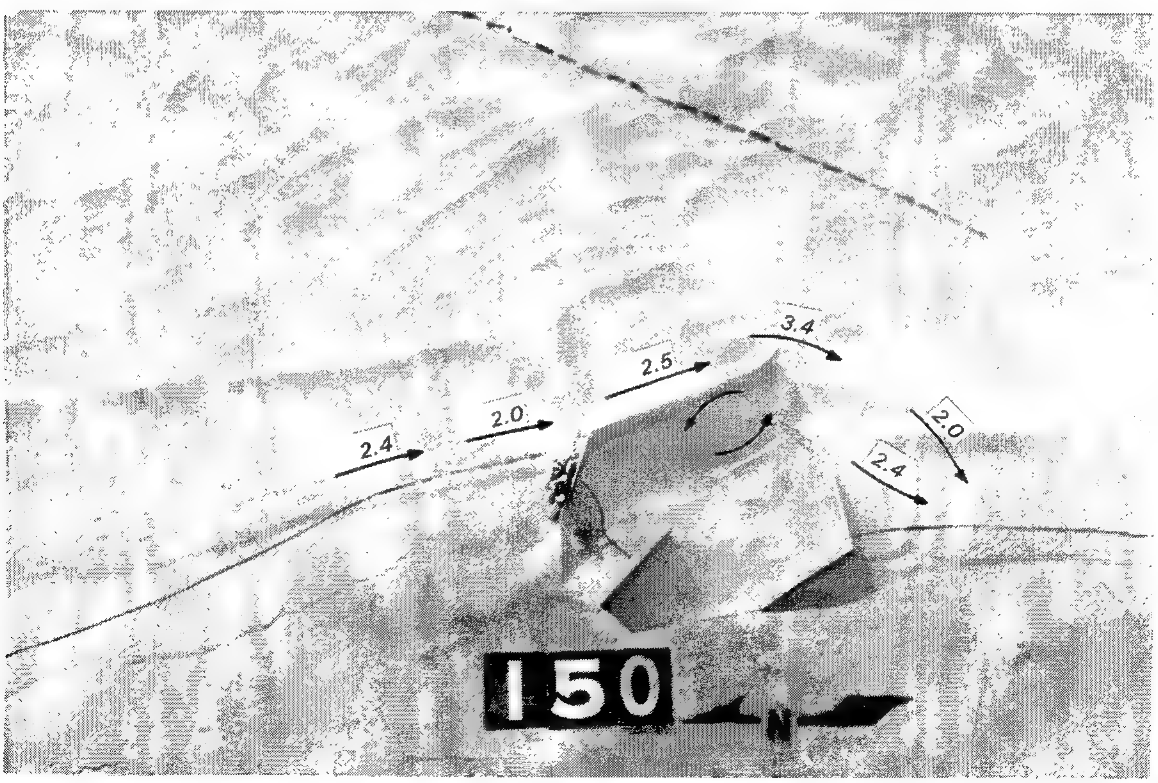



Photo 150. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 6.5-sec, 7.7-ft waves from 59 deg; swl = +1.7 ft (with riverflow conditions)

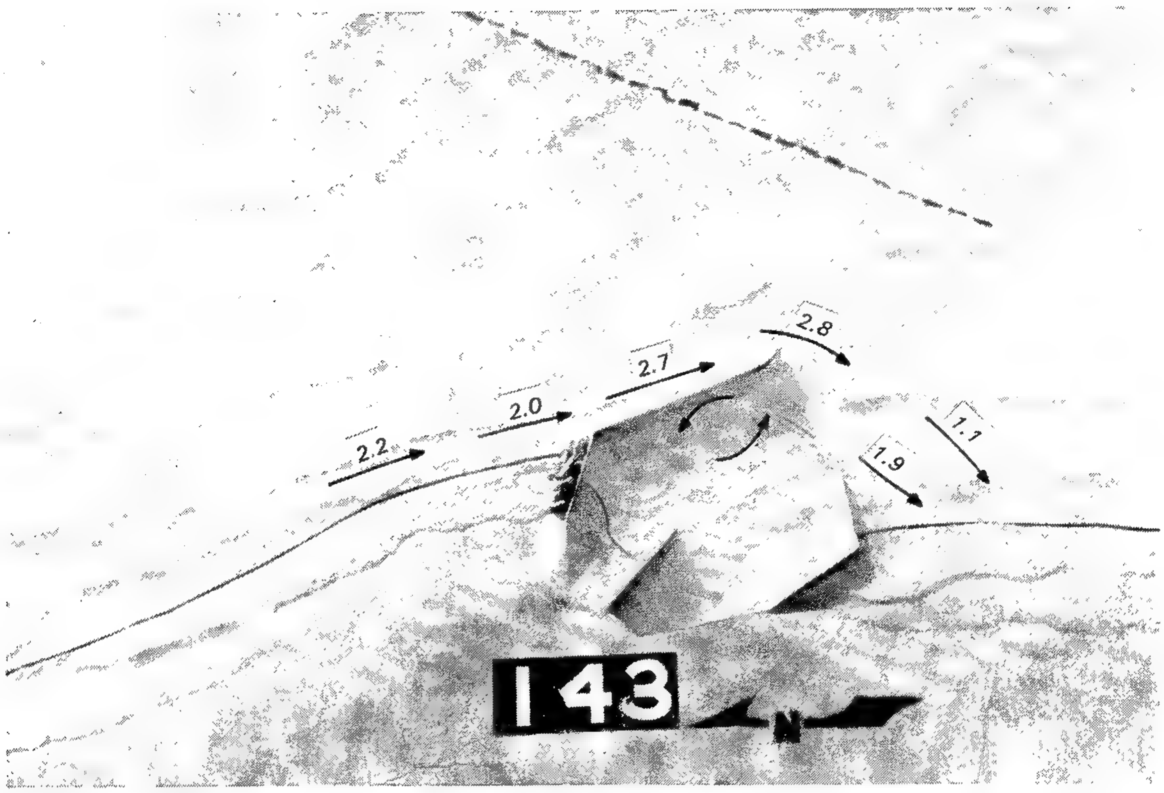



Photo 151. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 5.0-sec, 4.0-ft waves from 59 deg; swl = +3.5 ft (with riverflow conditions)

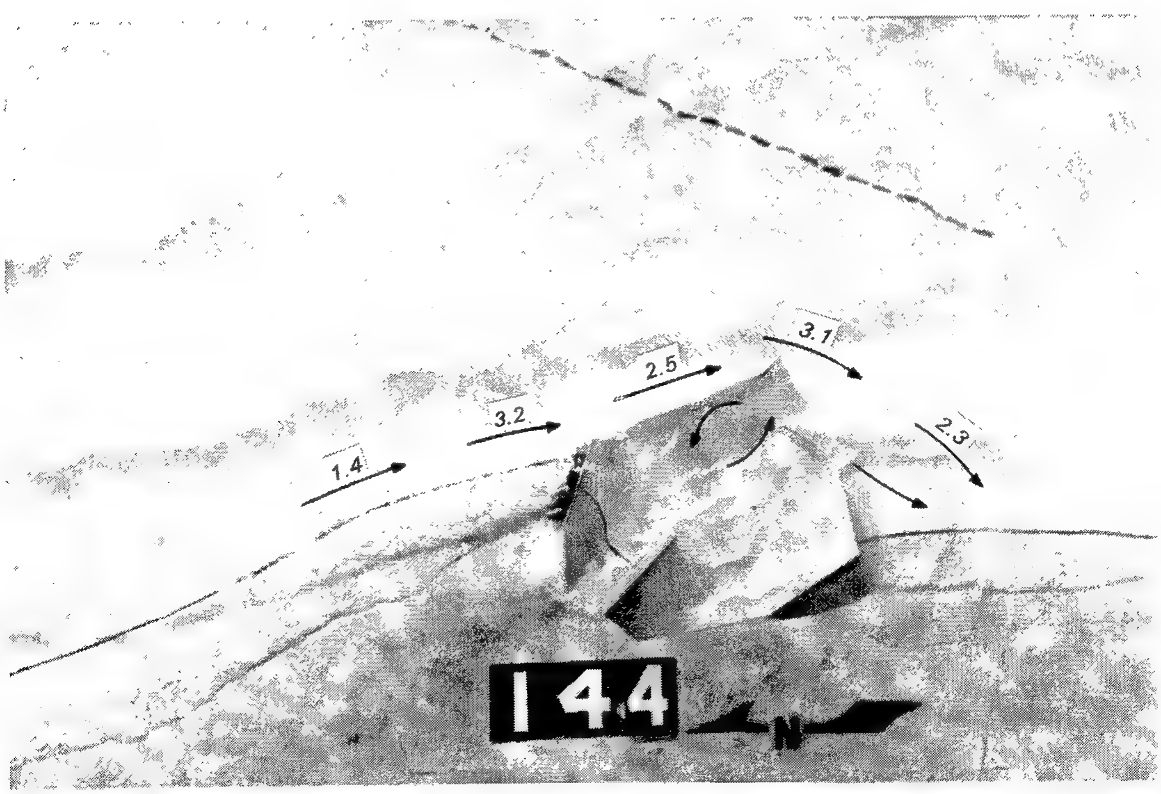



Photo 152. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 6.5-sec, 7.7-ft waves from 59 deg; swl = +3.5 ft (with riverflow conditions)


Photo 153. View of 17-m-long (90-ft long) speedboat leaving St. Clair River for Plan 10


Photo 154. View of 30-m-long (100-ft long) cabin cruiser leaving St. Clair River for Plan 10

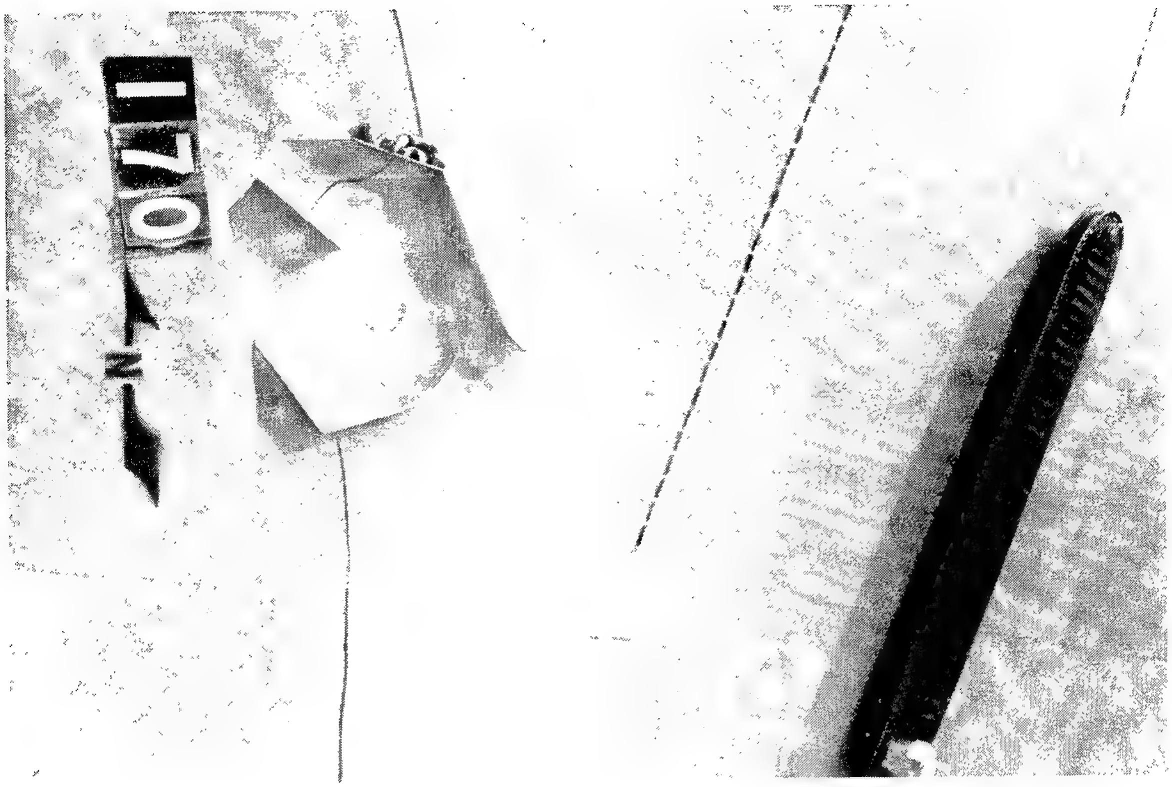


Photo 155. View of 183-m-long (600-ft long) ore carrier leaving St. Clair River for Plan 10

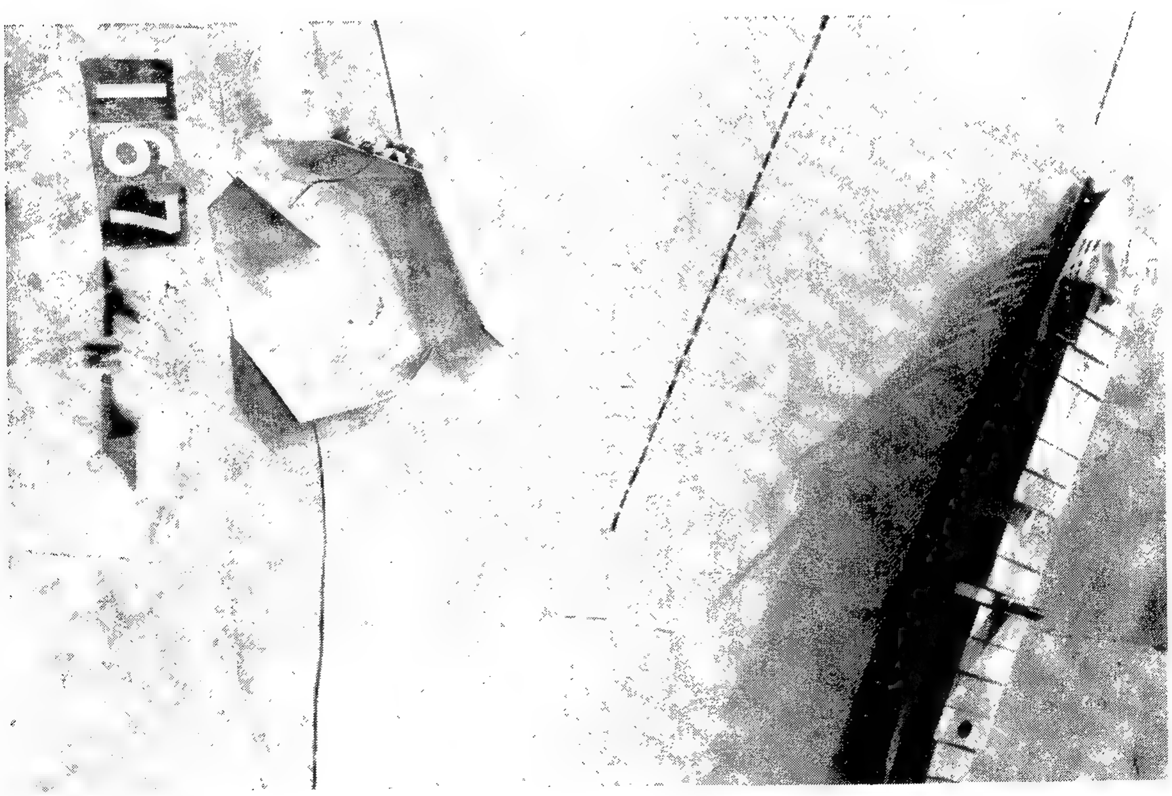


Photo 156. View of 210-m-long (690-ft long) container vessel leaving St. Clair River for Plan 10

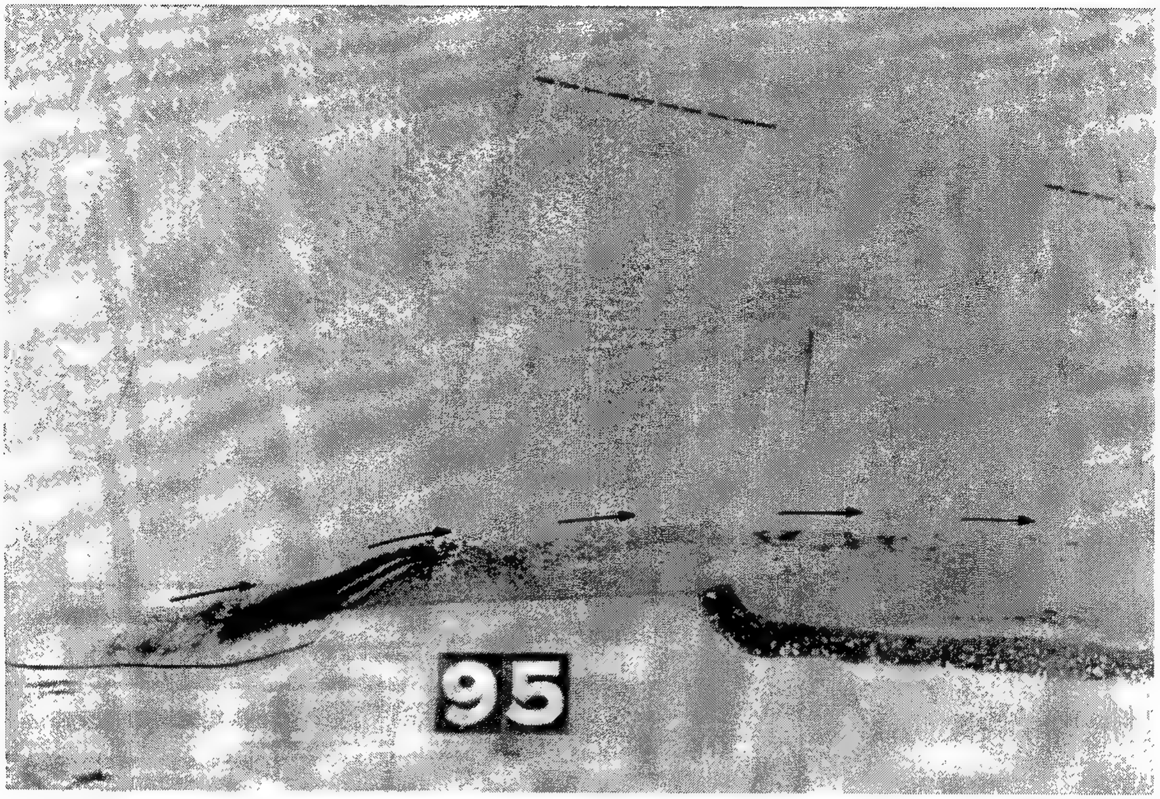



Photo 157. General movement of tracer material and subsequent deposits along shoreline downstream of harbor for existing conditions

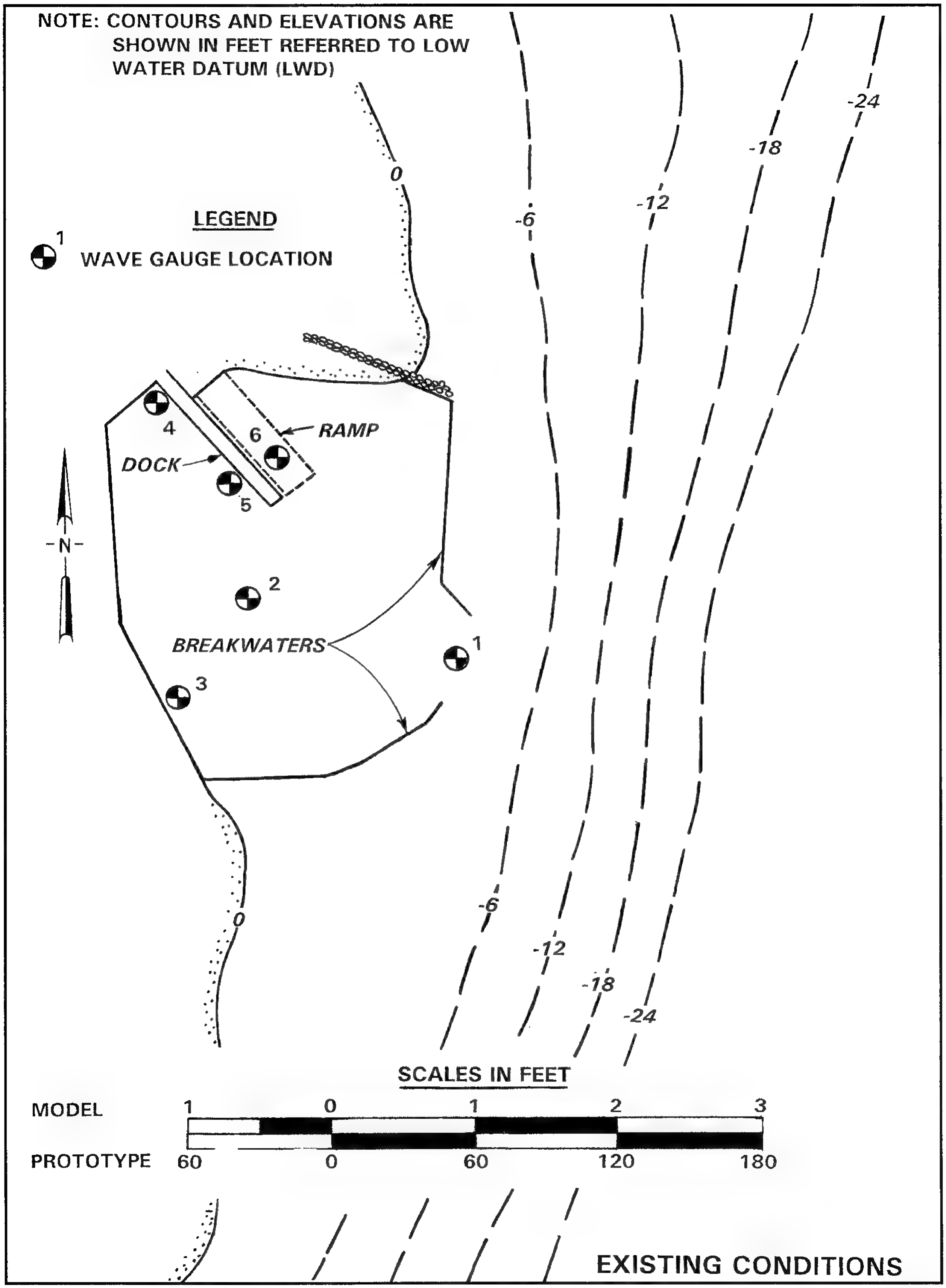

NOTE: CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)
LEGEND
WAVE GAUGE LOCATION
0
-6
-12
-18
-24
RAMP
DOCK
BREAKWATERS
1
2
3
4
5
6
N
SCALES IN FEET
MODEL
1 0 1 2 3
PROTOTYPE
60 0 60 120 180
EXISTING CONDITIONS

Plate 1

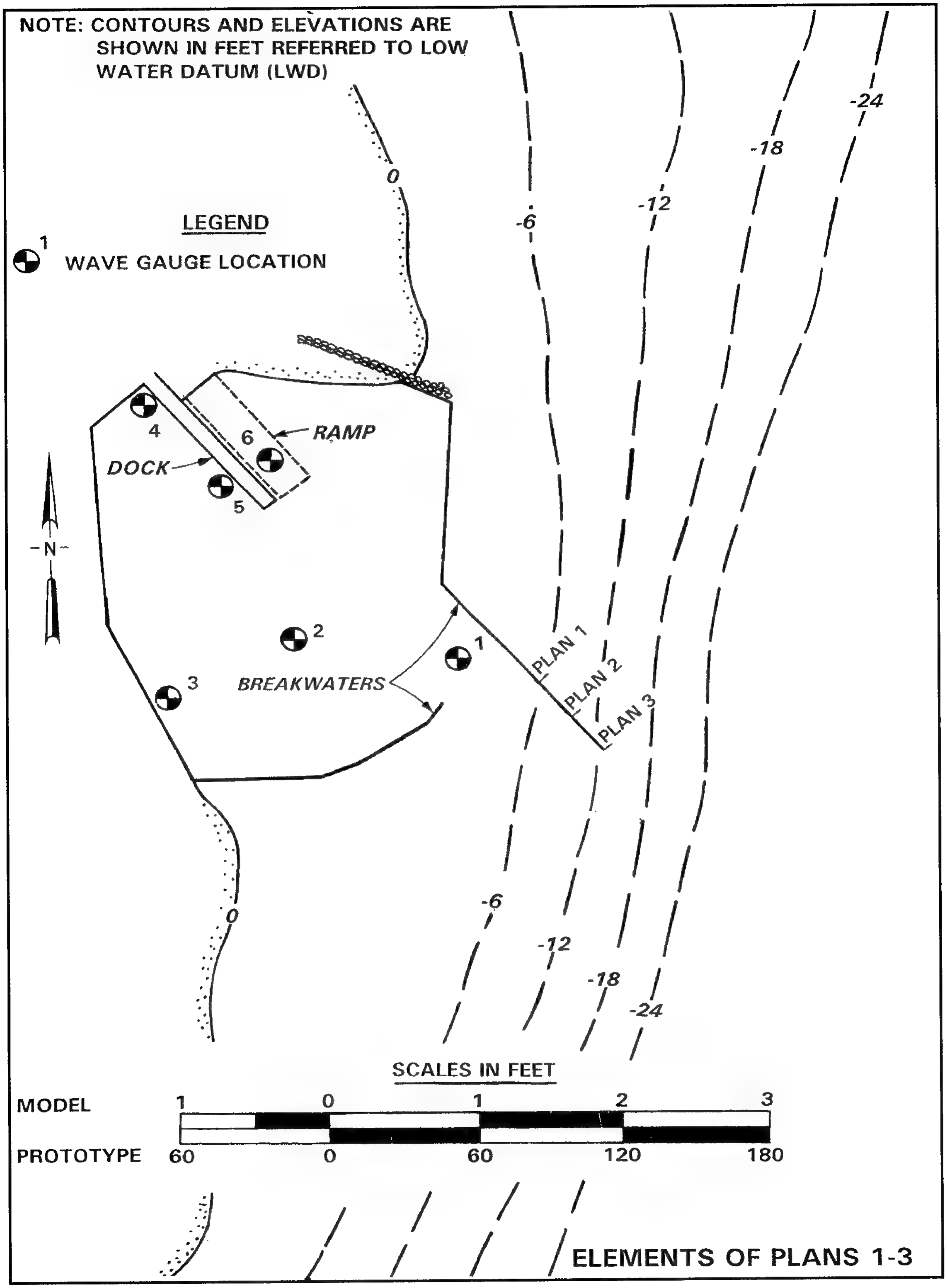
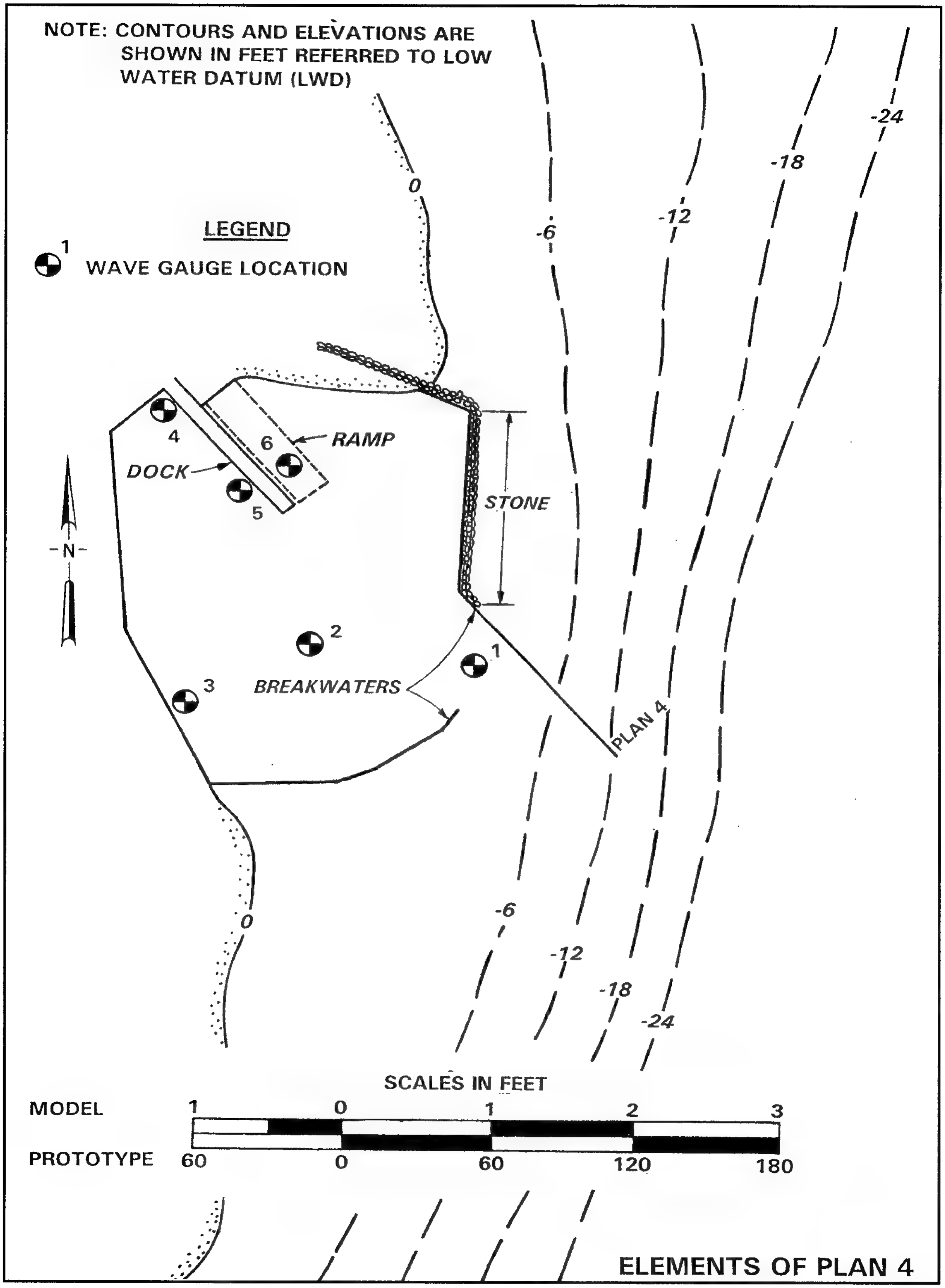
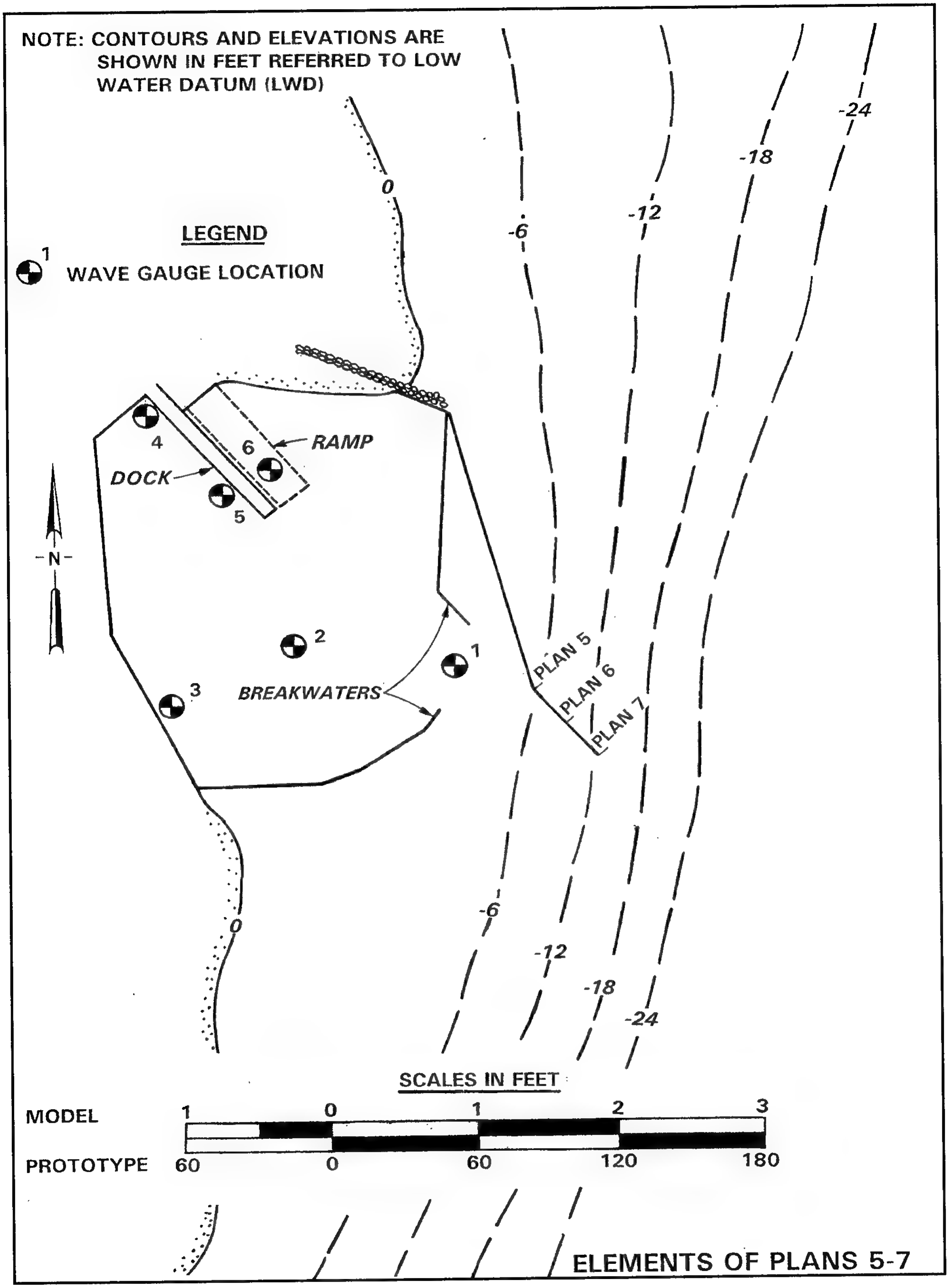

NOTE: CONTOURS AND ELEVATIONS ARE SHOWN IN FEET REFERRED TO LOW WATER DATUM (LWD)
LEGEND
1 WAVE GAUGE LOCATION
0
-6
-12
-18
-24
RAMP
DOCK
N
BREAKWATERS
PLAN 1
PLAN 2
PLAN 3
1
2
3
4
5
6
SCALES IN FEET
MODEL 1 0 1 2 3
PROTOTYPE 60 0 60 120 180
ELEMENTS OF PLANS 1-3

Plate 2



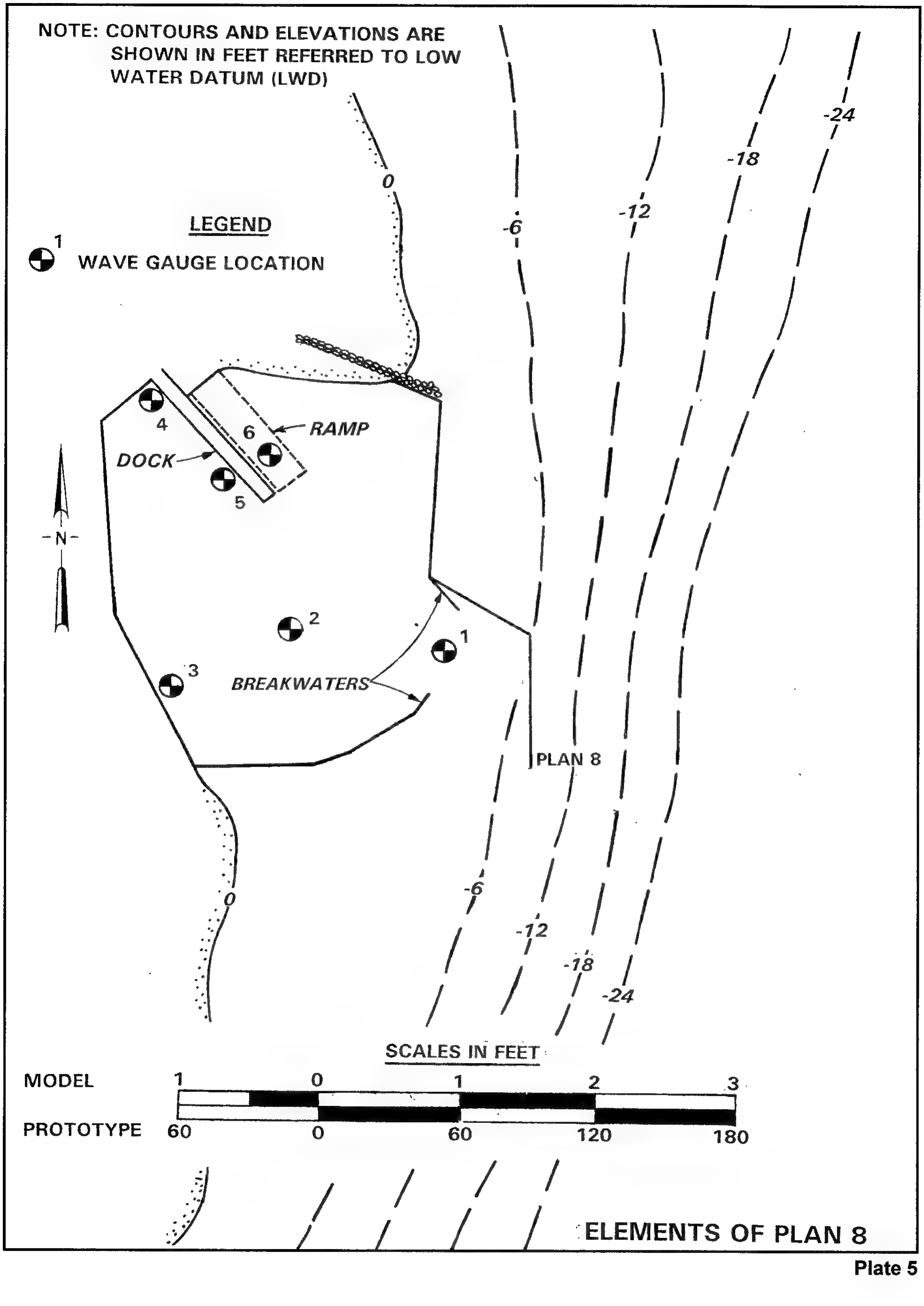

ELEMENTS OF PLAN 4

Plate 3

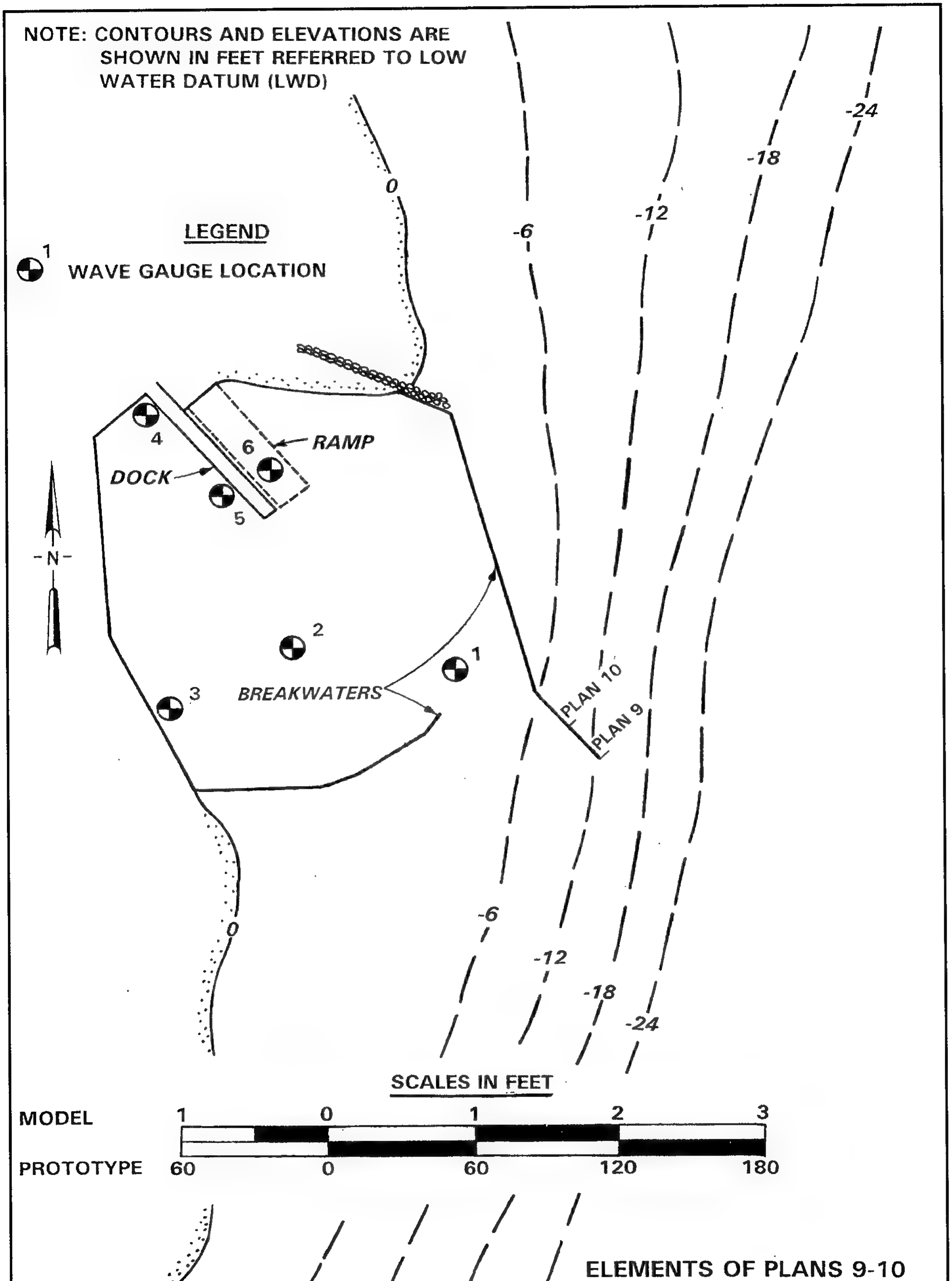



ELEMENTS OF PLANS 5-7

Plate 4

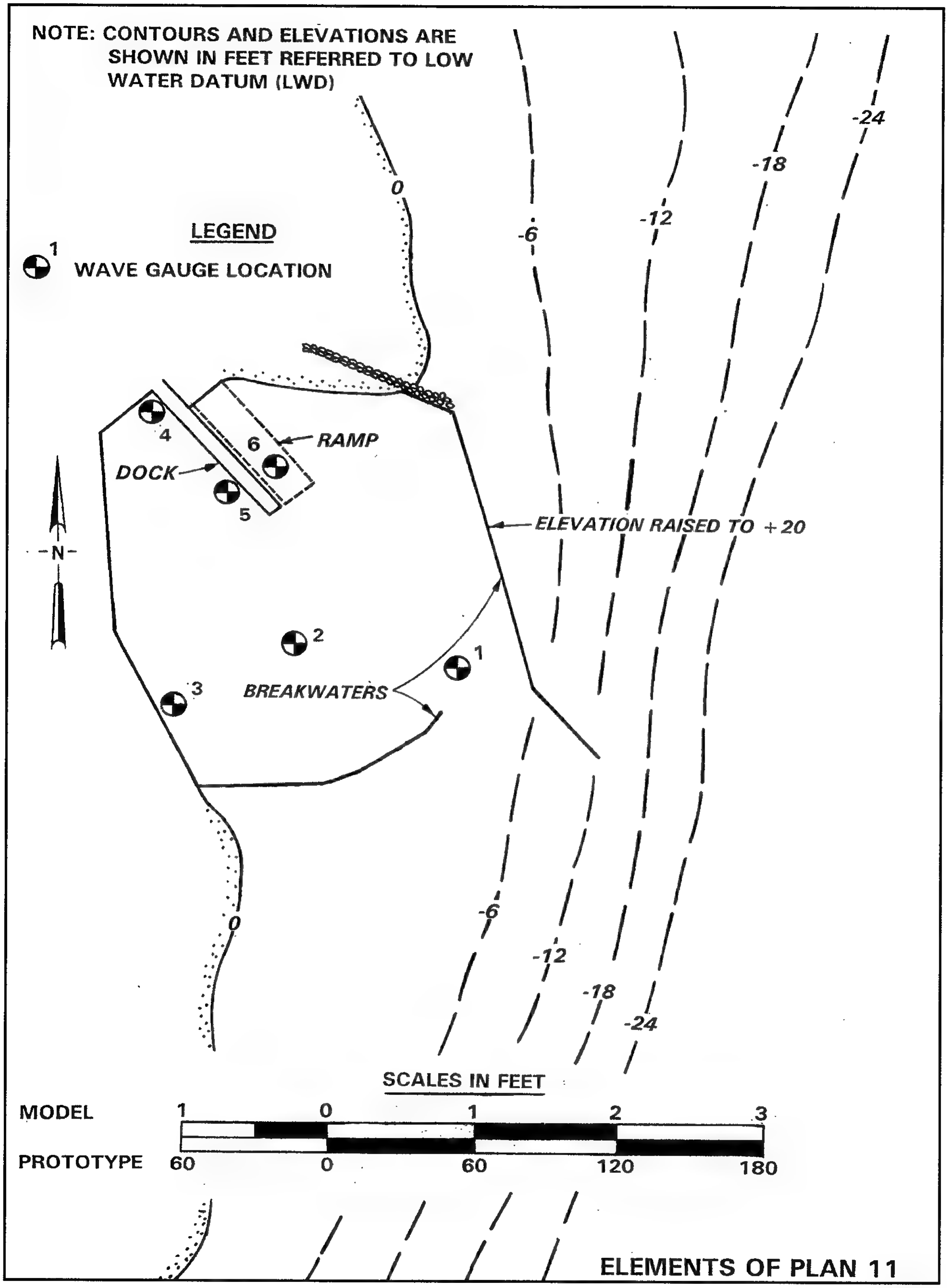



ELEMENTS OF PLAN 8

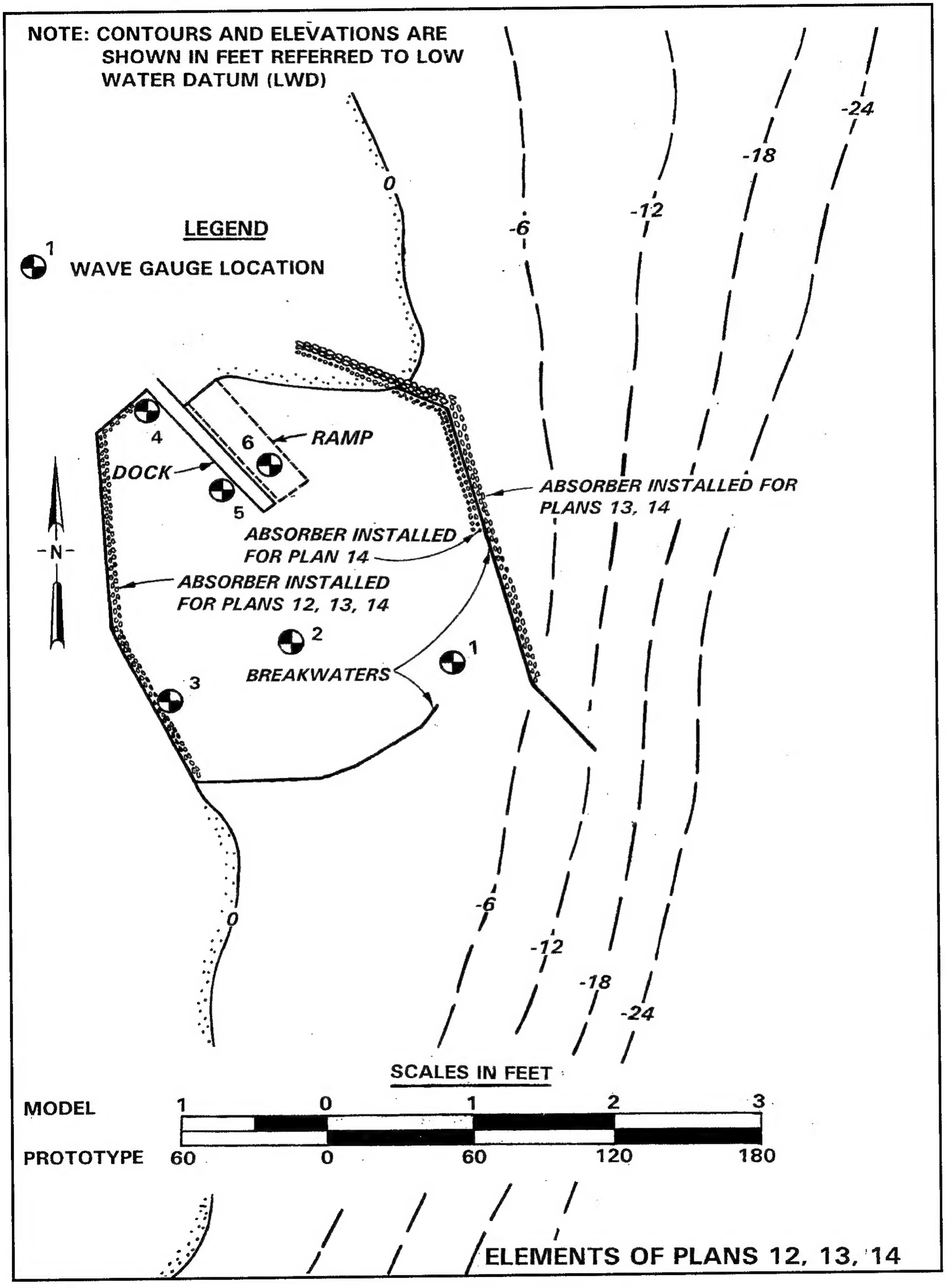


ELEMENTS OF PLANS 9-10

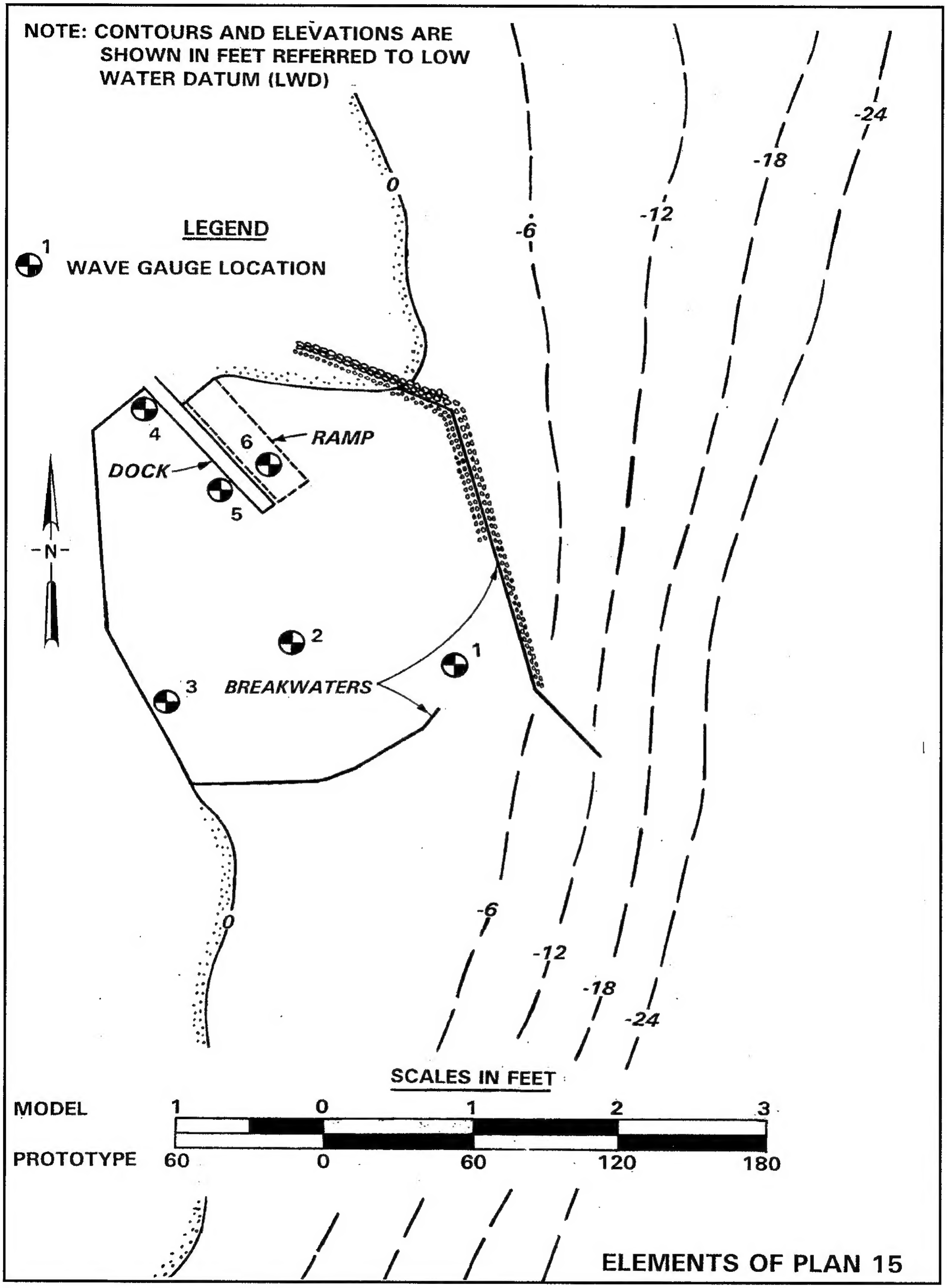
Plate 6



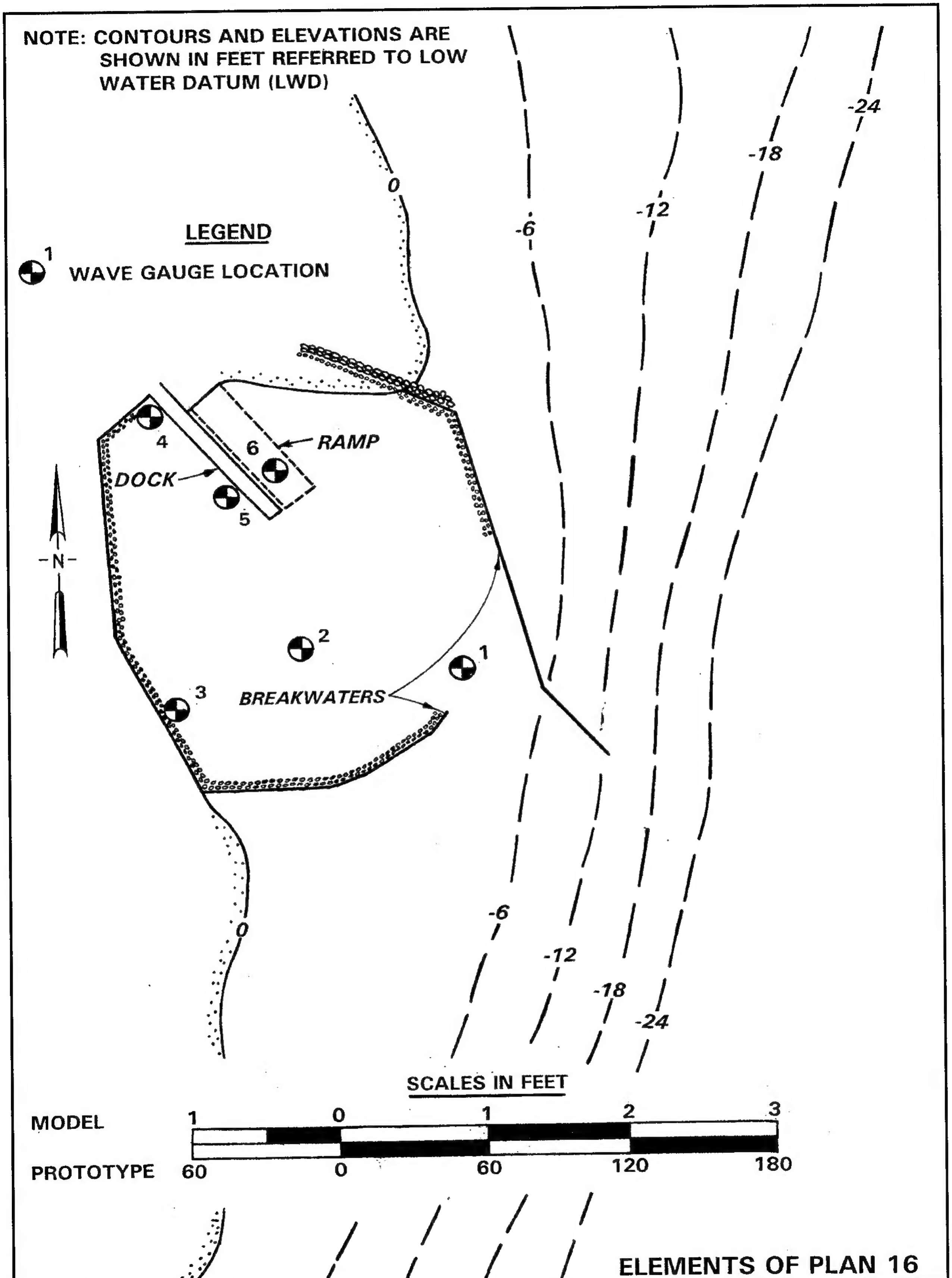

ELEMENTS OF PLAN 11




ELEMENTS OF PLANS 12, 13, 14



ELEMENTS OF PLAN 15




ELEMENTS OF PLAN 16

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The U.S. Coast Guard Station, Port Huron, Michigan, is located at the southern end of Lake Huron near the lake's transition to the St. Clair River. A co-located small boat basin used for berthing search and rescue vessels has experienced chronic shoaling since its construction 1931. Multiple basin configuration changes have been made with the intention of reducing shoaling and/or annual dredging requirements to an acceptable level and to reduce wave energy, which causes mooring problems in the harbor. The location of the basin at this dynamic lake-to-river transition site is particularly problematic because of the strong unidirectional currents that influence sediment transport and navigation into and out of the basin. A field study and sediment-transport analysis examined the bathymetry and hydrodynamics of lower Lake Huron as they relate to the shoaling and resonance problems inside the basin. In addition, a physical model study identified a modified basin configuration that reduces both entrance shoaling and undesirable wave energy in the basin.

**14. SUBJECT TERMS**

| | |
|---|---|
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| Hydrodynamics | Sedimentation |
| Physical model investigation | Vessel-generated waves |
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| River currents | Wave-induced currents |

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